AN ULTRA LOW-NOISE AC BEAM TRANSFORMER AND DIGITAL SIGNAL PROCESSING SYSTEM FOR CERN'S ELENA RING

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Abstract

CERN's 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). Essential longitudinal diagnostics required for commissioning and operation include the intensity measurement for bunched and debunched beams and the measurement of $\Delta p/\mathrm{p}$ for debunched beams to assess the electron cooling performance. The beam phase information is also needed by the Low-Level RF (LLRF) system.

The baseline system for providing the required beam parameters and signals is based upon two ultra-low-noise AC beam transformers and associated digital signal processing. The AC beam transformers cover different frequency regions and are an adaptation to the ELENA layout of those used in the AD. Two AC beam transformers will also be installed in the extraction lines to provide beam intensity measurements. The digital signal processing will be carried out with the leading-edge hardware family used for ELENA's LLRF system. The paper provides an overview of the AC beam transformer and associated digital signal processing.

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 further decelerate the beam injected from the AD at 5.3 MeV down to 100 keV so as to increase the number of useful antiprotons captured by the experiments by reducing the number of particles lost in 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.

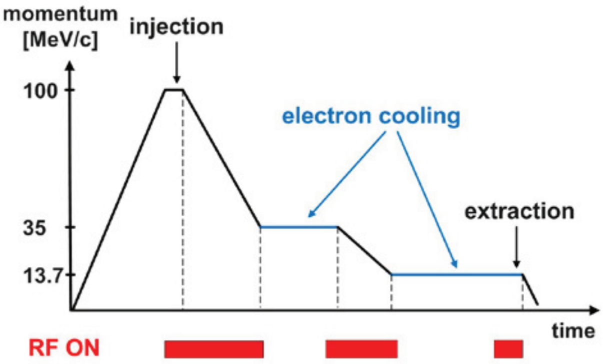

Figure 1: Schematic view of the ELENA cycle.

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. Beside the most challenging application of the described pick-up, the measurement of the beam intensity with Schottky diagnostics, this device will serve for many other applications such as the estimate of the momentum spread of coasting beams and bunched beam diagnostics

A distributed electrostatic pick-up [2] is studied as an alternative to the device presented here.

SYSTEM REQUIREMENTS

Functionality

Essential longitudinal diagnostics required for commissioning and operation include: a) the intensity measurement for bunched and debunched beams; b) the measurement of $\Delta p/p$ for debunched beams to assess the electron cooling performance; c) the tomoscope [3], which will provide a measurement of the beam shape, size and emittance; d) the analogue signals observation system, which will digitize and display the analogue signals. The beam phase information is also needed by the low-level RF system to implement the beam phase loop as well as the synchronisation loop at extraction. Bunch intensity has to be measured as a single-pass device in the extraction lines. The low frequency cut-off of the measuring device should be of about 3 kHz to measure the bunch length at the lowest value of revolution frequency. The bandwidth of the measuring device should be of 20 MHz or more to allow measuring the shortest bunch length; this is also desired to measure Schottky bands at high harmonics, thus allowing faster acquisition and better statistics [4].

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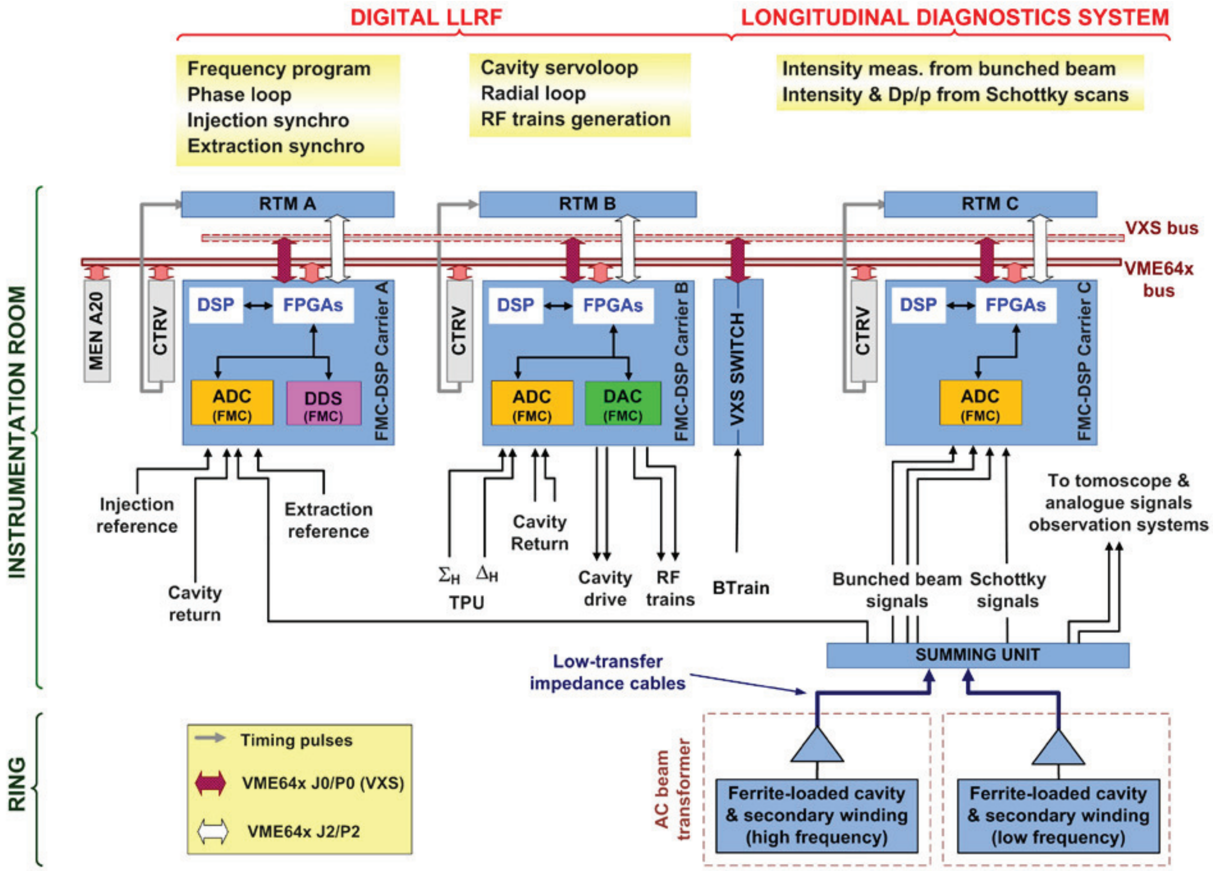

Figure 2: ELENA ring intensity and Schottky measurement system. Keys: **DDS** - Direct Digital Synthesiser (DDS); **ADC** - Analogue-to-Digital FMC board; **DAC** - Digital-to-Analogue FMC board; **RTM** - Rear Transition Module; **TPU** - Transverse Pick-Up; **CTRV** - Timing Receiver Module; **Men A20** – master VME board; **BTrain** - measured magnetic field. The blue and the FMC blocks are custom hardware designed by CERN's BE/RF group.

Space and Vacuum Constraints

Only up to 1 m in the ring and 50 cm in each extraction line can be dedicated to the longitudinal.

A design pressure of $3\cdot 10^{-12}$ Torr is required in ELENA to prevent beam blow-up due to the residual gas scattering, The ring hardware needs to be bakeable to a temperature of 200 degrees for special devices, and NEG-coated whenever possible.

SYSTEM OVERVIEW

The baseline system for providing the required beam parameters and signals is based upon an adaptation to the ELENA constraints of the system successfully deployed in the AD [5, 6, 7]. This consists of two ultra-low-noise AC beam transformers, covering respectively the 0.003-3 MHz frequency range (low frequency type) and 0.8-30 MHz frequency range (high frequency type) and associated digital signal processing.

Two AC beam transformers of the low-frequency type will also be installed in the extraction lines to provide bunch intensity measurements in single-pass mode.

Figure 2 shows a block diagram of the ring system, as it is currently foreseen. The analogue outputs of the two AC beam transformers in the ring are sent via low-transfer impedance cables to a summing unit located in the instrumentation room. This unit filters and adds together the AC transformer outputs to give a flat response over the whole 0.003 – 30 MHz bandwidth. The summing unit outputs are distributed to the various users of the signals, such as the longitudinal diagnostics system and the LLRF.

The advantages of the single gap magnetic pickup compared with a dual gap drift tube electrostatic pickup are: a) better Signal-to-Noise Ratio (SNR) for most of the frequency and momentum range; b) lack of vulnerability to charge-up due to lost particles [8]. This makes measurements possible for intensities much below nominal. The closed orbit PU system will however be conceived to also function for longitudinal Schottky measurements, and the vulnerability to lost particles charge-up addressed by the available redundancy [2]. Above the resonant frequency of the magnetic beam transformer, the signal-to-noise power spectral density ratio scales as $1/f^3$ (or -9 dB/octave), while for the dual gap electrostatic drift tube it scales as $1/f$ (or -3dB/octave) due to the unfavourable influence of the transit time factor at lower frequencies.

HARDWARE

AC Beam Transformer and Summing Unit

As in the AD, the AC beam transformer will consist of a doubly shielded, ferrite-loaded cavity with a ceramic gap in the beam pipe, a secondary winding and an ultra-low noise JFET head amplifier with low noise feedback connected to the secondary winding and mounted close to the cavity [5]. Figure 3 shows the ferrite loaded beam transformer and amplifier.

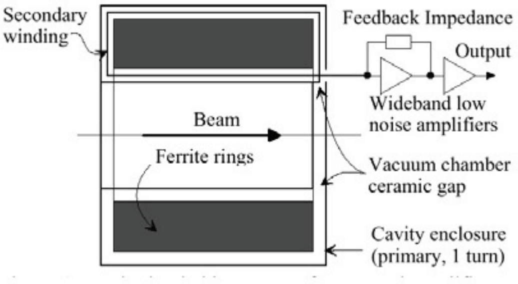

Figure 3: Ferrite loaded transformer and amplifier.

Two such transformers will be installed in section 2 of the ELENA ring, back-to-back to reduce the distance between the gaps and inter-connected via a bellow to reduce stresses on the vacuum flanges joining them. The total bandwidth covered by the combined devices will be 0.003 – 30 MHz. Figure 4 shows a picture of the two AC beam transformers successfully operating in the AD.

Figure 4: Picture of the two AC ferrite-loaded transformers installed and operational in the AD ring.

A partial redesign will be needed for several reasons. First, the total length of the combined high and low frequency transformers in the ring will be of 100 cm only, vs. the 112 cm allocated in the AD. As a consequence, only 9 active disks instead of the 10 present in the AD will be used. The inner diameter of the ferrite rings will be decreased from the 146 mm in the AD to 110 mm, to account for the smaller vacuum pipe used in ELENA. The outer diameter of the ferrite will be of about 180 mm, smaller than in the AD, thus reducing the global cost and weight. An outer-to-inner diameter ratio higher than in the AD would increase the inductance per meter and increase the low-frequency response. However this increase is not worth the additional cost and weight. The thickness of the shielding copper wall will be reduced from 7 to 6 mm and the outer-to-inner cavity insulation gap from 11 to 8 mm. The head amplifiers gain will be controlled in real time, thus taking the place of the second stage amplifiers currently used in the AD system.

Second, the step-up ratio of the high-frequency device will be changed from 2:1 (in the AD) to 1:1, thus reducing the noise current by a factor 4 in power and increasing the signal –to-noise ratio. This will also introduce a higher frequency separation between low and high-frequency devices, allowing to measure Schottky signals at high harmonics, hence with better statistics, even at low energies.

Third, the transfer function of the head amplifiers connected to the low-frequency device will be changed to provide a flat baseline for a duration of 6 µs, thus allowing the bunch intensity measurement of each of the four bunches extracted in one turn. This will be obtained by lowering the transfer function low-frequency cut-off.

Finally, the beam transformers will have to withstand a bake-out temperature of 200 degrees. Since the bake-out of the machine is expected to happen rarely, the head amplifiers will simply be removed during bake-out.

Ring-to-Processing-System Signals Transmission

The dynamic range of the AC beam transformer output is of more than 100 dB, since it includes both strong correlated signals for a bunched beam and weak Schottky noise for a debunched beam. An additional challenge is the need to minimise the noise pick-up in the cable that goes from the output of the head amplifier to the signal processing system, as it will reduce the Signal-to-Noise Ratio (SNR). The baseline solution includes using a low transfer impedance, magnetically loaded cable, as it was successfully done in the AD and is planned in other ELENA systems with similar needs [2]. Other solutions have been considered. For instance, the signals could be digitized directly in the ring and transmitted via optical fibre, thus making them insensitive to noise pick-up. The signals could then be converted again to analogue format and distributed to the different systems requiring them. The summing unit could also be moved to the ring, thus allowing for shorter cables hence lower noise pick-up. These solutions would however require studies as well as new developments. For these reasons, the baseline solution remains to implement a copy of what already implemented in the AD.

Digital Acquisition and Processing System

The digital signal processing will be carried out with the leading-edge hardware family that will be used for ELENA’s LLRF system. Figure 2 gives an overview of the main building blocks, which are detailed elsewhere [9]. The longitudinal diagnostics system will be hosted in the same crate as the LLRF, thus allowing a cheaper solution.

The RF clock used for sampling the system inputs is a signal at a high harmonic of the revolution frequency, obtained from the LLRF via the VXS Switch board. A revolution “TAG” (single or double) signal is also distributed; this marks each revolution turn, thus allowing to follow the bunch during deceleration, and synchronises in phase all elements of the system.

SOFTWARE

The FPGAs and the DSP hosted by the DSP-FMC-Carrier board will share the digital signal processing implementation. The system will receive in real time from the LLRF: a) the value of the cavity voltage, to determine the beam status (bunched vs. debunched); b) the revolution frequency value, to calculate the start of the bunched-beam integration window.

Digital Signal Processing for Debunched Beams

The debunched-beam digital signal processing is conceptually the same as that deployed in the AD [5]. This is based on windowing the input data and calculating and averaging several Fast-Fourier Transforms (FFTs). The noise offset measured in a dedicated cycle without beam will be subtracted from the averaged FFT vector to avoid including it in the intensity calculation. The spectral density will then be integrated and the longitudinal parameters obtained from it, as shown in Figure 5.

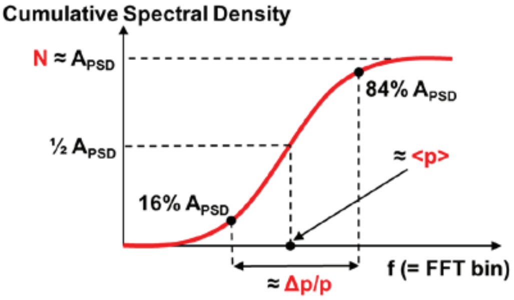

Figure 5: Debunched-beam parameters calculation.

Digital Signal Processing for Bunched Beams

Bunched beam intensity measurements were obtained in the AD by measuring the RF amplitudes at the bunch frequency and at its second harmonic. The intensity was then obtained approximating a Gaussian spectral envelope. This method will be available in ELENA despite significant measurement errors are obtained for long, non-Gaussian bunched.

The new hardware allows a bunched beam measurement that is bunch length independent. This consists in integrating the bunch shape, once the baseline is identified, and subtracting the baseline value itself, as shown in Figure 6. The intensity value will be obtained by averaging a user-selectable number of bunches.

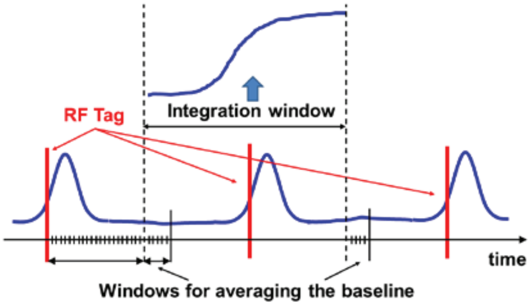

Figure 6: Integration window for bunched beams.

The baseline value is determined by sampling the baseline and averaging its samples, making sure that the bunch is not extending into that region. The analogue revolution “tag” signal and the revolution frequency value distributed by the LLRF are used to determine the start of the integration window.

MEASURED INTENSITY CALIBRATION

There are two independent methods of absolute calibration for the intensity measurements.

First, the bunched and debunched beam intensity measurements in the ring use the same cavity and amplifier chain but have a different dependency on the gain, respectively linear and quadratic. The gains are correct if measured intensities are identical.

Secondly, the transformers on the extraction lines can be calibrated on an absolute charge scale by discharging into a resistive current divider a known capacitor charged to a known value. This can be used for calibration of the ring system by comparing intensities measured just before extraction and extracted ones, under the assumption of close to 100% extraction efficiency.

CONCLUSIONS AND OUTLOOK

ELENA is a challenging machine, owing to its low energy, low intensity beam and small size. The intensity and debunched-beam parameters measurement are essential diagnostics for commissioning and operation. A plan based on adapting to ELENA the AC beam transformers successful operational in the AD has been established. The digital signal processing will be carried out by the leading-edge hardware family to be deployed in several CERN synchrotrons, thus allowing for easier maintenance and better spares management.

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