THE AD SCHOTTKY SYSTEM AND FUTURE EVOLUTIONS

Maria Elena Angoletta, CERN, Geneva

Abstract
An innovative system to measure antiproton beam intensity, momentum spread, mean momentum and tune in CERN’s Antiproton Decelerator (AD) is described. This system is based on a state-of-the-art Digital Receiver (DRX) board, consisting of 8 Digital Down-Converter (DDC) chips and one Digital Signal Processor (DSP), and on ultra-low noise pick-ups. The system provides real-time information characterising the machine performance; it has been used for troubleshooting and to fine-tune the AD, thus allowing further improved performance. This paper gives an overview of the system hardware and software, together with hints on its possible future evolution.

CARE-N3-HHH-ABI Workshop

Chamonix, December 11-13, 2007
1. **INTRODUCTION**

A new CERN machine for low energy antiprotons production, named the Antiproton Decelerator AD [1], is operational since 2000. Antiprotons from a target, bombarded with an intense beam from the 26 GeV Proton-Synchrotron (PS), are fed to the AD where they are decelerated in several ramps to a momentum $p$ of about 100 MeV/c. Figure 1 shows the basic AD cycle; bunched-beam deceleration ramps are interspersed with plateaus, where the beam is cooled at fixed $p$ and revolution frequency $f_{REV}$.

![Figure 1: The momentum $p$ during the AD basic cycle (2002 version).](image1)

The intensity of its antiproton beam varies from some $5 \times 10^7$ particles at 3.5 GeV/c to some $3 \times 10^7$ at 100 MeV/c. Traditional DC beam transformers do not work at these low intensities, hence ultra-low-noise longitudinal [2] and transverse [3] pick-ups are used.

The new digital-receiver-based AD beam-diagnostic system acquires and processes the data generated by these pick-ups. The system measures beam current intensity, momentum spread, mean momentum and transversal tunes throughout the AD cycle. It therefore enables a real-time evaluation of cooling and deceleration performance during the AD cycle.

2. **SYSTEM OVERVIEW**

On the magnetic plateaus the beam is debunched for stochastic or electron cooling and longitudinal beam properties (intensity, momentum spread and mean momentum) are measured by FFT-based spectral analysis of Schottky signals. For bunched beams, the intensity is obtained by measuring the amplitude of the fundamental and second RF Fourier components; the bunch length is also derived. The tune is measured by the Beam Transfer Function (BTF) method [4]. Additional information can be found in [5,6].

Figure 2 gives an overview of the system. The inputs from the two longitudinal pick-ups (LPUs), optimised respectively for high (HF LPU) and low frequency (LF LPU), are filtered and added together by a summing unit to give the total input over the whole frequency range. The resulting signal is amplified by a variable-gain, remotely-controlled second-stage amplifier. After a low-pass filter stage, the signal is digitised by an ADC VME board. The data are digitally down-converted and processed by a Digital Receiver (DRX) board, which is...
set up before each measurement. The horizontal and vertical (TPUH/V) transversal PUs are devoted to tune measurement by the BTF method. The noise generator MG produces the analogue excitation used for BTF measurements.

Figure 2: Schematic view of the new digital-receiver-based system for the measurement of antiproton beam parameters.

Finally the software task running in the PowerPC (PPC) VME board collects, post-processes and stores the data for later display. Additionally, the PPC acquires from the RF and the stochastic cooling systems the information needed to optimise the choice among various user settings. Users access the system, to evaluate data and to set various parameters, through the standard Control and application layers.

3. HARDWARE

3.1 Longitudinal pick-up

Two LPUs provide the frequency bandwidth 0.1 MHz to 16 MHz required for the measurement of Schottky signals and beam intensity. They also improve the S/N ratio by lowering the overall noise floor. The noise power spectral densities of the two LPUs are given in Figure 3 and Figure 4 as functions of frequency and are summarised in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Total response bandwidth/MHz</th>
<th>Low noise bandwidth/MHz</th>
<th>Low noise value / pA/Hz$^{1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF LPU</td>
<td>0.25 – 30</td>
<td>[1 - 3 ]</td>
<td>1.5</td>
</tr>
<tr>
<td>LF LPU</td>
<td>0.02 - 3</td>
<td>[0.1 – 1 ]</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 1: Nominal characteristics of the HF and LF LPUs.
The LPUs are high-Q resonant devices, hence with a minimised Johnson noise. They are broad-banded by an active feedback, around the head amplifier, which simulates a "noise-free" resistor in parallel with the resonant circuit, as shown in Figure 5. The design of the LPUs and the corresponding head amplifiers ensures that the total equivalent input noise, in a part of the bandwidth, is dominated by the cavity Johnson noise. This can be seen in Figure 3 and Figure 4. Such bandwidth is indicated as the low-noise bandwidth in Table 1.
Figure 5 The HF LPU ferrite-loaded beam transformer and amplifier.

The outputs of the two LPUs are filtered and added together by the PU Summing Unit, to give a flat frequency response over the 0.02-30 MHz bandwidth. The low frequency pick-up signal is low-pass-filtered, the high frequency pick-up signal high-pass-filtered, giving the required bandwidth when the two are summed.

3.2 Transversal pick-up

Two electrostatic, transversal pick-ups have been constructed, for the vertical and for the horizontal plane, respectively. Each 1m long electrostatic PU is resonant at 5.6 MHz. The pre-amplifier has been designed so that, in a band around the resonance frequency, the Johnson noise from the losses in the coil is the dominant noise source of the system. To achieve the highest possible Q (low losses) of the resonant circuit, the PU has been designed with the coil inside the vacuum chamber. The high Q resonant circuit is detuned by a feedback around the pre-amplifier, making the input impedance appear like a 350 Ω resistor working at a temperature of less then 13 K. The principle of the same as that used in the longitudinal pick-ups, described in paragraph 3.1. Detuning the resonant circuit makes the PU broad-banded enough to always have a betatron sideband in the low noise part of the response from 5.3 MHz to 6.2 MHz. Figure 6 shows the construction details of a transversal pick-up and Table 2 gives their nominal characteristics.

Figure 6: Transversal pick-up – construction overview.
<table>
<thead>
<tr>
<th>Low noise bandwidth/MHz</th>
<th>Low noise value / pA/Hz(^{1/2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPU H/V</td>
<td>[5.3 – 6.2 ]</td>
</tr>
</tbody>
</table>

*Table 1: Nominal characteristics of the TPU PUs.*

3.3 Digital Signal Processing Hardware

3.3.1 ADC Board

The ADC board is a customised version of the Pentek 6441 model, a dual channel, 12-bit, board that operates at sampling rates of up to 41 MHz. Two analogue input signals are first amplified and then low-pass filtered prior to being fed to the Analog Devices 12-bit A/D chip. The digital signal is multiplexed so that both signals are made available on two different flat cables (Upper and Lower). An external clock controls the board, so as to change the ADC sampling frequency \(f_s\) according to the beam state.

Initial off-line testing of the 6441 ADC showed that the measured S/N ratio was over 15 dB worse than what was listed in the original manufacturer specifications. It was found that the additional noise came from the board analogue input front-end. This major drawback was overcome by developing an in-house front-end which bypassed the input amplifier and the low-pass filter. The trade-off was the need to add an external filter on the analogue signal path before its digitisation. In this way, the S/N ratio was improved by 13 dB on average. Based on this solution, the ADC board manufacturer later developed a “low-noise” version of the board analogue front-end, which is now commercially available.

3.3.2 Digital Receiver Board

The digital receiver board is a commercial off-the-shelf VME board [7,8] that hosts 8 Harris HSP50016 Digital Down Converters (DDC) and one TI TMS320C40 Digital Signal Processor (DSP). This board is in charge of parallel data acquisition, independent digital down conversion and processing of up to 4 digitiser inputs. Figure 7 gives a schematic version of the board. The digitised inputs are pre-processed by the DDC chips, by digitally translating (*downmixing*) the input signal to DC, then zooming (*decimation*) on the frequency window of interest. Both the bandwidth and the centre \(f_{LO}\) of the frequency window are user-selectable. Each DDC is connected to a FIFO memory where data are stored. From the FIFOs the data are then retrieved and processed by the DSP. The board is equipped with several memory banks, of which the Global Memory is visible from the VMEbus and is used to retrieve processed data.
Figure 7: Schematics of Pentek’s 6510 DRX board. Shown at the top is an example of digital zoom on the window of interest and DDC sample decimation.

4. DIGITAL SIGNAL PROCESSING

4.1 Longitudinal bunched signals

For bunched beams, the intensity is obtained by measuring the amplitude of the fundamental and second RF Fourier components. The bunch length is also derived from this measurement. Figure 8 gives an overview of the data processing method.
The ADC $f_S$ is proportional to $f_{REV}$, thus allowing to track the beam when its revolution frequency changes. At each turn $m = 0, 1, 2$, the intensity time profile $I(t)$ of a single bunch is approximated, in the interval $[(m-\frac{1}{2})/f_{REV}, (m+\frac{1}{2})/f_{REV}]$, by a parabola:

$$I(t) = \frac{3}{4\sqrt{2}} \frac{I_0}{\tau \cdot f_{REV}} \left(1 - \frac{t^2}{2\tau^2}\right)$$

(1)

where $I_0$ is the DC current intensity per bunch and $2\tau$ is the FWHM.

The experimental Fourier coefficients $J_k$ (k=1, 2, ...) are calculated and then fitted with a truncated series of $f/f_{RF}$:

$$J_k = I_0 \cdot h \cdot \left\{2 - \Delta \cdot \left(\frac{f}{f_{RF}}\right)^2\right\}$$

(2)

where $h = f_{RF}/f_{REV}$ is the RF harmonic number. $I_0$ and $\Delta$ are therefore obtained, and thus the bunch size $\tau$:

$$\tau = \frac{1}{2 \cdot \pi \cdot f_{REV}} \sqrt{\frac{5\Delta}{2}}$$

(3)

Integration of the beam profile over time gives the total number $N$ of particles circulating in the machine, i.e. the beam intensity:

$$N = \alpha_R \cdot \frac{I_0 \cdot h}{f_{REV}}$$

(4)

The DRX actually uses only two data points $A_k = J_k/G$ with $k=1,2$. These are labelled DDC1 and DDC2, respectively, in Figure 8. The $A_k$ are then fitted with a truncated series of $x = f/f_{RF}$:

$$y = A_0 \cdot (2 - \Delta \cdot x^2)$$

(5)

hence $I_0$ and the bunch size can be derived.

4.2 Longitudinal debunched signals
On the magnetic plateaus the beam is debunched for stochastic or electron cooling and longitudinal beam properties (intensity, momentum spread and mean momentum) are measured by FFT-based spectral analysis of Schottky signals. Figure 9 shows the data processing method.

\[ N \sim A_{PSD} \]

\[ \frac{1}{2} A_{PSD} \]

\[ 16\% \ A_{PSD} \]

\[ 84\% \ A_{PSD} \]

\[ \sim \Delta \frac{p}{p} \]

\[ f \ (\text{FFT bin}) \]

\[ f \sim \frac{\alpha_U A_{PSD}}{G_U f_{REV}^2} \]  

\( \alpha_U \) is a calibration constant and \( G_U \) is the global system gain. From the width \( \Delta f \) of the PSD curve at a 2\( \sigma \) height, the momentum spread \( \Delta p/p \) is:

\[ \frac{\Delta p}{p} = \frac{1}{n \cdot f_{REV} \cdot \eta} \cdot \Delta f \]

\( \eta = \left( \frac{\gamma_{TR}^2 - \gamma^2}{(\gamma_{TR} \gamma)^2} \right), \gamma = E/E_0, \gamma_{TR} = 4.75 \) and \( n \) is the harmonic number.

4.3 Transversal signals

The beam is excited with a band-limited M-shaped noise, by means of a transverse damper deflector, and recording the deflector excitation and the transverse beam response. These are then FFT-processed to yield the tune. Figure 10 gives an overview of the data processing method.

**Figure 9:** Longitudinal Schottky integrated power.
Figure 10: Principle of the BTF measurement. The tune is determined mainly from the BTF phase spectrum.

It is possible to measure tunes at lower intensities and during the ramps, by keeping the sampling frequency $f_s$ equal to a multiple of $f_{REV}$. The M-shaped excitation is chosen so as to minimise transverse beam blow-up, by setting $f_C$ very close to a betatron frequency. The system calculates five spectra: the transfer function (magnitude and phase), the coherence function and the power spectral density of the beam and of the noise. The user uses a dedicated application program to determine the machine tune from these spectra, thus the tune is measured in a semi-automatic way.

5. MEASUREMENT EXAMPLES

Figure 11 shows typical intensity and momentum spread $\Delta p/p$ measurement over an AD cycle, together with the RF status. When the RF is ON the beam is bunched and the intensity is measured with the method described in paragraph 4.1. On the contrary, when the RF is OFF the beam is debunched and intensity and $\Delta p/p$ are measured with the method described in paragraph 4.2. Measurements carried out during the bunched-debunched beam transition are intrinsically inaccurate. Debunched beam data are more affected by noise, whereas bunched beam signals, which are much larger, are less influenced. Towards the end of the cycle, instabilities and/or bad statistics generate an “explosion” of the measured power, thus generating overestimations of the beam intensity.
Figure 11: Intensity (red trace), revolution frequency (blue trace) and \( \Delta p/p \) (green trace) in a typical AD cycle (screenshot taken in 2002). The RF status (ON/OFF) is shown in orange at the bottom of the picture.

Figure 12 shows a typical screenshot of the BTF application program. The five spectra available to the user are shown in the figure bottom part, as a function of the FFT bin number. The setup parameters or each measurement are shown in the top part. The user clicks on the bin corresponding to the tune and the application calculates the corresponding tune from the bin number and from the measurement setup parameters.

Figure 12: BTF on bunched beam @ ramp 2 (screenshot taken in 2004).
6. FUTURE EVOLUTION

A new compact ring for post-AD antiproton deceleration & cooling has been proposed. This ring is called Extra Low ENergy Antiprotons (ELENA) ring and its preliminary cost and feasibility study report can be found in [9]. A system with the same capabilities of the AD Schottky system is needed; its implementation has been proposed based upon the same hardware successfully deployed in Low Energy Ion Ring (LEIR) LLRF [10, 11]. Its basic building blocks are a DSP/FPGA motherboard and several daughtercards (MDDS, SDDS, DDC) and the proposed system, implementing LLRF as well as and diagnostic systems is shown in Figure 13. Advantages over the AD Schottky system implementation include a reduced cost per channel. Additionally, the BTF noise is generated digitally instead of with a dedicated analogue hardware.

![Figure 13: LLRF and intensity-tune measurement systems proposed for the ELENA ring.](image)

A similar system can be envisaged for the AD, if a consolidation plan is required.

7. CONCLUSION AND FUTURE WORK

The AD Schottky system described in this note provides data that are essential for a smooth AD operation as well as for the experimental users. The same data processing on a more flexible hardware is proposed for the new compact ring for post-AD antiproton deceleration & cooling, ELENA. A similar system can be envisaged for the AD, if a consolidation plan is required.
REFERENCES