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TURN-BY-TURN POSITION MEASUREMENTS AT CNAO WITH THE LIBERA SPARK HR PROTOTYPE

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Abstract

CNAO in Pavia is one of the first centers for hadron therapy in Europe, treating patients since 2011. The center is an international reference for a whole new concept of machines being constructed for this purpose. The synchrotron BPM electronics is based on analog boards that compute the ratio between difference (Delta) and sum (Sigma) signals from the shoebox pickup, later acquired by digital cards. Although the system operates reliably, it just calculates the position with 1 kHz rate, while the revolution frequency ranges from 0.5 to 3 MHz. To extend the measurement possibilities for these new hadron synchrotrons, Instrumentation Technologies is developing a data acquisition system capable of acquiring the pickup signals with 125 MSps ADCs and calculating bunch-by-bunch positions of the accelerated beam. The first prototype was tested at CNAO: the turn-by-turn beam position was analyzed off line, at different energies and positions with both Protons and Carbon ions beam. This paper presents the results achieved with the Libera system and compares them with the measurements of the current CNAO front end.

INTRODUCTION

As demand for proton and carbon ion facilities increases, more and more attention is put in to the optimization of their core accelerators. Beam diagnostics are one of the critical components which are used to understand and improve these machines. This article focuses on the beam position monitor (BPM) system and presents the measurements performed at CNAO, comparing the data collected with the existing BPM system with the Libera Spark HR prototype.

The CNAO BPM system is based on shoebox pickups and an analog front end which computes the delta and sigma signals. The analog signals are later digitized and used to calculate the beam position with 1 kHz rate. Libera Spark HR is BPM readout electronics prototype, being developed with the purpose of computing the beam position with bunch-by-bunch data rates. To achieve that it acquires the BPM signals at high rates (i.e. 125 MSps) and stores them in the internal memory to be further processed in the FPGA. In order to make the results from two systems comparable, the existing CNAO digitizer was replaced by a 100 MSps Lecroy digital oscilloscope.

In order to calibrate the two systems, tests were firstly performed with a test bench consisting of a spare BPM pickup with 5 wires crossing its section in five different positions. A sine signal was injected into each wire to simulate the beam and compare the read positions.

After calibration the two systems were installed on BPM pickup located in the machine high dispersion region, with pickup signals split between the two readouts. Both proton and carbon ion beams were used and the position of the beam was controlled via the LLRF system. The results presented in the article are focusing on the Proton beam measurements.

LIBERA SPARK HR PROTOTYPE

The goal of the Libera Spark HR prototype (see Fig. 1) is to provide position and charge information from the circular hadron machines with bunch-by-bunch rate [1]. The specific characteristics of the hadron synchrotrons such as variable RF frequency, bunch length and signal intensity, require the RF front-end to offer a linear frequency response. This is achieved with a carefully designed low pass filter with 35 MHz bandwidth, based on the solution developed for Libera Hadron [2] and implemented in the prototype.

Figure 1: Libera Spark HR.

Data Processing

After the data is digitized, the system stores the ADC data in a large internal buffer with 8 million of sample, equivalent to 64ms of data. As this is a prototype evaluation, the data processing is done externally with Matlab. The ADC data belonging to different bunches is isolated and separately processed [2]. For each of the four BPM signals, their amplitude is calculated with a energy-based formula. Amplitudes are later used in a delta over sigma formula which calculated the beam position.

Performance Measured in the Laboratory

Measured in the laboratory, Libera Spark HR position resolution is close to 2 µm rms (kx = ky = 100 mm) for a single-bunch beam structure (pulse FWHM = 100 ns).

MEASUREMENTS AT CNAO

The measurement setup at CNAO consisted of both instruments connected to the same BPM pickup with typical beam position around -25 mm. Only the two BPM signals from the horizontal plane were acquired. The data from Libera Spark was transferred to a PC via Ethernet

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while the CNAO front end Delta/Sigma signals were acquired directly from the LeCroy oscilloscope and transferred to a PC. The acquisition time in both cases was 1 ms, with acquisition rate of 125 MHz for Libera Spark and 100 MHz for the oscilloscope.

In all the tests the measurements were done at the end of the acceleration cycle, also called “Flat top”. This phase usually before the extraction is characterized by stable beam conditions at the nominal energy required. The beam position was changed from measure to measure controlling the position set-point with the LLRF system which implements the feedback with reference to a pickup which is on the other side of the machine. Being the optics symmetrical, a similar deviation was expected in the position of the observed BPM pickup. The beam was displaced in 5 different positions spaced by 5 mm.

The number of acquired turns during the acquisition time of 1 ms depends on the beam energy. Acquired signals from the CNAO front end and Libera Spark HR can be seen in Figure 2.

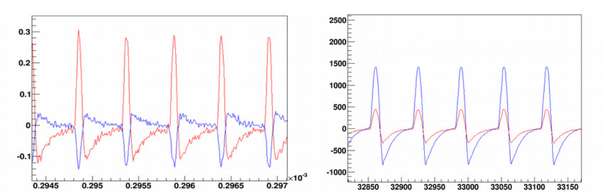

Figure 2: Sigma (red) and Delta (blue) acquired by the CNAO front end electronics (left figure). Right (red) and Left (blue) electrodes acquired by the Libera electronics.

DATA ANALYSIS WITH CNAO OFFLINE ALGORITHM

The ADC data acquired from both systems was stored in C++ ROOT [3]. The data processing is divided in two steps: first data is manipulated to obtain a “clean” signal with the following operations:

- The signals from the two electrodes are summed and subtracted to obtain the Sigma and Delta signals
- The integral signals (corresponding to the bunch charges) are calculated integrating the Sigma and Delta signals separately – see Figure 3.
- The bunch data is discriminated by finding the two local minimals before and after the bunch peaks.
- The offset subtraction is applied to the signals. The offset is computed bunch by bunch as a linear regression between the two local minimals corresponding to one bunch, and is subtracted point by point.

The beam parameters are calculated with the “clean” data:

- For each bunch the integral of Sigma and Delta, proportional to the beam charge, are computed using a fixed threshold
- The ratio between Delta and Sigma is multiplied by the mechanical sensitivity to calculate the beam position
- The amplitude of each bunch is computed by using the Sigma integral signal

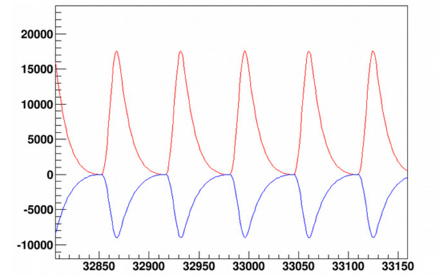

Figure 3: Integrated delta and sigma data.

Position standard deviation for CNAO front end and Libera was calculated for each beam displacement, and is presented in Figure 4.

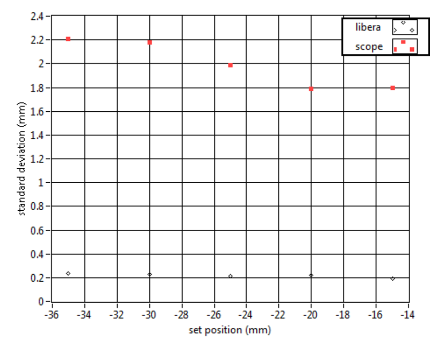

Figure 4: Standard deviation for CNAO front end and Libera (on X axis there is set position in mm and on Y axis standard deviation).

DATA ANALYSIS WITH LIBERA BUNCH-BY-BUNCH ONLINE ALGORITHM

The difference between the Libera BPM and CNAO front end is that Libera is a digital system which digitalizes directly the pickup outputs, while CNAO front end combines digitalization with analogue signal summing and subtraction.

The output of the CNAO front end is delta and sigma signals, while Libera Spark processes directly signals from the pickups. Therefore a different processing concept is used.

- From the ADC data from individual channels, the samples belonging to individual bunches are identified (see Figure 5)
- For each channel and for each bunch, the amplitude is calculated with sum-of-squares formula:

$$V_A = \sqrt{\sum_{PROC\ WIN.\ START}^{PROC\ WIN.\ END} A^2} \qquad V_C = \sqrt{\sum_{PROC\ WIN.\ START}^{PROC\ WIN.\ END} C^2}$$

$$X = K_X \frac{(V_A' - V_C')}{(V_A' + V_C')} + X_{OFFSET}$$

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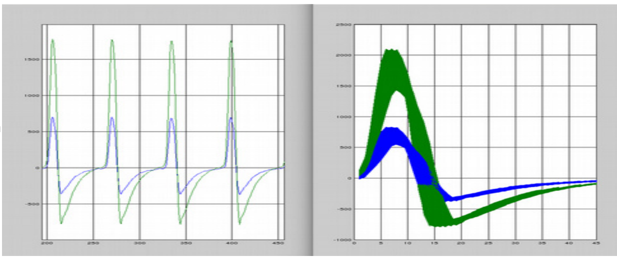

Figure 5: Left plot presents digitalized signals A and C directly from pickup. Extracted bunch informations from 1 ms data acquisition (ADC data) is presented on the right plot (~1900 extracted bunch signals are ploted).

The processing described above was firstly implemented in Matlab script which processed the Libera Spark ADC data. In a second test, the ADC data was fed in to the digital signal processing (DSP) algorithm already implemented in Libera Hadron FPGA [2], using an FPGA simulation tool.

Negligible discrepancies in the position calculation were found after comparing results from both processing (Matlab and FPGA simulation tool).

INTERPRETATION OF RESULTS

The results from the measurements are summarized in Table 1 which presents the position measurements and Table 2, presenting the position standard deviations. Standard deviation was calculated from the whole batch of data, taking in account beam fluctuations.

Table 1: Position Measurement Results

Set beam position [mm]	CNAO front end CNAO DSP [mm]	Libera Spark HR CNAO DSP [mm]	Libera Spark HR Libera DSP [mm]
- 35	-32.91	-31.66	-29.06
- 30	-27.79	-26.81	-24.68
- 25	-22.52	-22.02	-20.31
- 20	-17.63	-17.49	-16.37
- 15	-12.5	-12.62	-11.67

Table 2: Standard Deviation Results

Set beam position [mm]	CNAO front end CNAO DSP [mm]	Libera Spark HR CNAO DSP [mm]	Libera Spark HR Libera DSP [mm]
- 35	2.21	0.24	0.14
- 30	2.18	0.23	0.10
- 25	1.99	0.21	0.12
- 20	1.79	0.22	0.11
- 15	1.79	0.19	0.08

Few considerations can be done about the presented results. First of all the positions achieved with Spark HR and CNAO front end are slightly different (Table 1). This can be corrected introducing an offset (-1 mm) and a scaling parameter (0.933) in the CNAO reconstruction. This could be due to the signal splitting and not equal cables used for connecting both devices. The reconstructed position after rescaling is equal.

Standard deviation of the Libera reconstructed position is better that the CNAO one. This can be explained with the fact that Libera is “all in one” low noise system, avoiding the long cables between the front end and the back end electronics (oscilloscope) what was the case of CNAO front end. Furthermore digital oscilloscope noise ratio and dynamics are not optimal. However it needs to be mentioned that this is not the complete system of data acquisition presently used at CNAO (complete system includes front end and back end analog modules that optimize data acquistions before PXI cards which then calculate the beam position with 1 kHz rate).

It is worth to mention also that signal level provided to the Spark HR instrument was very low (1/10 of full scale).

Minor discrepancies in slope linearity were found when comparing CNAO algorithm and Libera algorithm results. Further studies will be needed in order to understand these phenomena.

CONCLUSION

From the results achieved with the tests, the idea of using Libera Spark as a BPM readout system for hadron therapy machines has been confirmed. The tests provided clean results with a turn-by-turn beam position resolution of few hundred micrometers, with still some margin for improvement.

Some minor discrepancies were observed between the measurements with the Libera bunch-by-bunch algorithm and the CNAO algorithms: these differences will be further studied.

We would like to emphasize successful collaboration between CNAO beam diagnostics group and Instrumentation Technologies. Thanks to the successful measurements, the Libera Spark for hadron circular machines can be now finalized in a commercial instrument.

REFERENCES

[1] Instrumentation Technologies, “New line of Libera products”, Libera Workshop 2016, Solkan, Slovenia, July 2016

[2] Instrumentation Technologies, “Libera Hadron User Manual v1.03”, Solkan, February 2018

[3] fair-center.eu website: http://www.fair-center.eu/public/what-is-fair/accelerators.html