S-BAND CAVITY BPM READOUT ELECTRONICS FOR THE ELI-NP GAMMA BEAM SOURCE

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Abstract

The Extreme Light Infrastructure – Nuclear Physics Gamma Beam Source (ELI-NP GBS) facility will provide an high intensity laser and a very intense gamma beam for various experiments. The gamma beam is generated through incoherent Compton back-scattering of a laser light off a high brightness electron beam provided by a 720MeV warm LINAC. The electrons are organized in compact trains with up to 32 bunches, each separated by 16ns. To optimize the laser-electron interaction and therefore the generation of the gamma rays, one big challenge is to precisely monitor the trajectory of each electron bunch.

To match this requirement, at the interaction point two S-band cavity beam position monitors will be used, and the related readout system should perform bunch-by-bunch position measurements with sub-µm resolution. Using 500MS/s ADC converters and dedicated data processing, the readout system proposes an alternative measurement concept. In this paper the architecture of the system, the implemented signal processing and the results of the first laboratory tests will be presented.

INTRODUCTION

The ELI-NP accelerator facility employs a warm C-band electron LINAC [1]. At every injection, up to 32 electron bunches are accelerated and delivered to two interaction points (IP) with energies of 280MeV and 720MeV. The beam structure at the interaction point is represented in Figure 1.

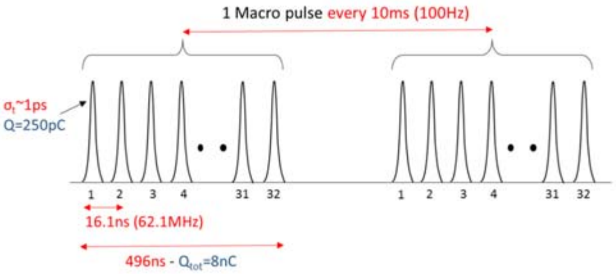

Figure 1: Electron beam structure at the interaction point.

In order to align the beam with the laser at the IP, the position of each bunch should be measured with µm resolution, in the range of ±1mm. For this purpose four low-Q cavity beam position monitors (BPMs) will be installed immediately before and after the IPs [2].

The cavity BPM pick-up is the same BPM16 used at PSI [3]. It consists of one reference cavity and one position cavity, with low quality factor (Q=40) and a resonant frequency of 3.284GHz. This makes sure that the signal excited by each bunch will decay fast enough to not interfere with the signal coming from the next bunch: this is necessary condition to perform individual bunch measurements.

THE READOUT ELECTRONICS

The concept and a first prototype of readout electronics was presented in [4] and further developed into a commercial readout electronics called Libera CavityBPM, shown in Figure 2.

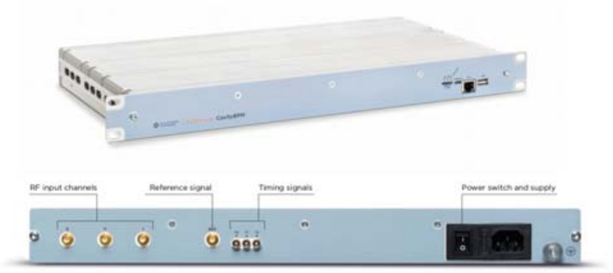

Figure 2: Cavity BPM readout electronics.

The cavity signals are processed by an RF front-end, which filters out the unwanted frequency components. A variable attenuation stage is used to adjust the position full-scale and to optimize the signal level depending on the beam conditions (e.g. charge, position). Finally the signals are down-converted to an intermediate frequency (IF) in the 2nd Nyquist zone, and filtered again to remove the signal components which are outside of the bandwidth of interest. A block-scheme of the RF front-end is shown in Figure 3.

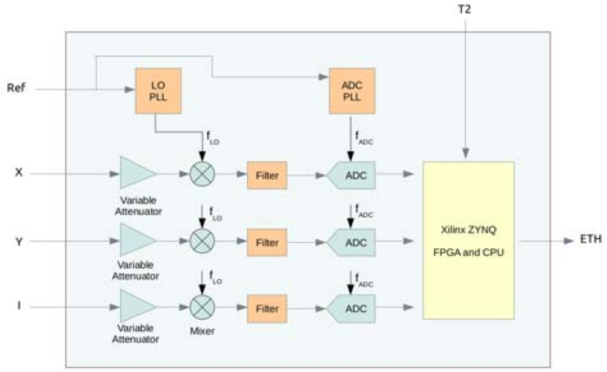

Figure 3: RF front-end of the readout electronics.

The local oscillator (LO) frequency component and the A/D converters sampling rate (ADC) are generated by two PLLs which are locked to the accelerator reference frequency of 62.087MHz.

500MS/s Digitizer and Bunch Decoupling

The signals are later digitized by 14bit dual A/D converters, sampling at 500MSps. The high sampling rate is required to collect enough information from each bunch: with a separation of 16.1ns, only 8 samples per bunch are available. The ADC data is continuously transferred through serial interfaces to a Xilinx ZYNQ 7035 System-on-Chip which provides all the necessary computing resources: FPGA, CPU and internal shared memory. Every time a new injection happens, the trigger signal enables the storage of up to 4k ADC samples in the memory of the device, ready to be further processed.

Once the signals are digitized, the samples belonging to different bunches need to be separated. In the proposed solution, a 100-bin FIR filter is used to extract the individual bunch signals from their superposition, and to compress them to occupy exactly 8 samples. The filter is called *"Deconvolution filter"* and its coefficients are calculated starting from the single-bunch response of the cavity. An example of how the filter works with a single bunch input signal is presented in Figure 4.

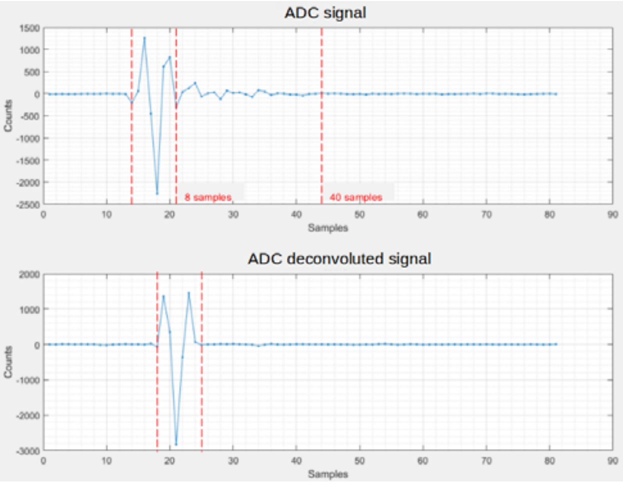

Figure 4: Bunch separation through deconvolution filter.

Position Calculation and Calibration

Once the data of each bunch is separated, it is possible to calculate the amplitude (V_x, V_y, V_r) associated to each cavity signal through a sum-of-squares formula and to calculate the absolute position value with the equations:

$$X = K_x \frac{V_x}{V_r} \qquad Y = K_y \frac{V_y}{V_r}$$

where K_x, K_y are calibration constants which depend on the sensitivity of the cavities and on the relative value of the variable attenuators. As the position is calculated through the ratio between two channels, each error on one of the channels is reflected directly in the instrument accuracy. For this reason a calibration procedure is required to characterize the attenuation and phase shift introduced by the variable attenuators and the installation setup (cables, connectors, etc...), and to correct his effect when calculating the amplitudes.

Finally, to determine the sign of the position, the phase relation between the position and the reference cavity, and this is done in parallel through I/Q demodulation.

LABORATORY SETUP AND MEASURES

A delicate aspect in the validation of the Cavity BPM readout electronics is how to reproduce in the laboratory an input signal which is a good approximation of the signal produced by the beam. The test setup is prepared by INFN-LNF and is presented in Figure 5.

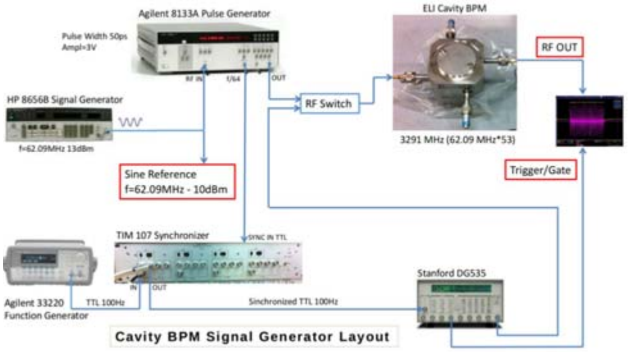

Figure 5: Laboratory test-setup.

The best way to to generate a signal which has the same resonant frequency and decay time as the real one, is to use directly the same BPM16 cavity which will be used in the machine. A pulse generator feeds pulses to one port of one position cavity and from the other port the resonant output signal is split in two and connected to the position and reference cavity inputs of the electronics. The pulse generation is continuous and a gate is used to select only a certain number of pulses, from 1 to 32 to reproduce the real beam structure.

Although the setup produces a very good approximation of the beam signal, there are some limits compared to the real measurement conditions:

- the high insertion loss of the cavity limits the signal level at the instrument input;
- the pulse generator is not ideal interims of cleanliness amplitude fluctuations;
- splitting the output of the cavity results in two input signals with correlated noise;

Single-Bunch Measurements

In the single-bunch measurements, the signal shown in the upper part of Figure 4 is provided to the system. The deconvolution filter is not used, therefore 40 ADC samples are considered in the calculation of the signal

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amplitudes. The internal attenuators are set at the same level and the input signal is equally split among the position and reference cavity. In this way the measured position is always at the full scale, in this case equal to 1mm. For the analysis, the ratio between the standard deviation of the position and its mean value is considered.

Figure 6 presents how this ratio depends on the phase difference between the two input channels considered. For each point, 100 independent measurements were taken in order to calculate the statistics.

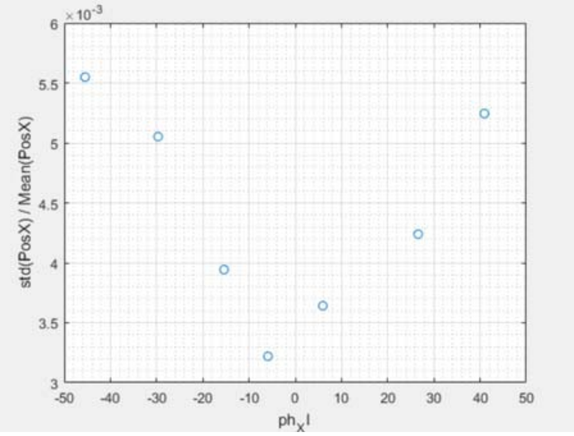

Figure 6: Performance in single-bunch mode.

As it is possible to see, the best performance is achieved when the two signals are perfectly in phase: this point is equivalent to a 3.2µm RMS over a full scale of one mm. When the phase changes the ration goes up to 5.5%. This effect has still to be fully understood, however one possible reason is the fact that with no phase shift, the correlated noise gets cancelled by the position calculation ratio. This is not true any more when the phase is changed. This aspect will require further analysis on a real machine.

Bunch Train Measurements

A train of 32 bunches was generated with the setup, and the input signal for the cavity is shown in Figure 7.

Figure 7: Multi-bunch input signal for the cavity.

In order to process this signal and calculate individual bunch positions, the deconvolution filter was used. Each bunch position along the train was individually analyzed and the results are presented in Figure 8.

It is possible to see that the behaviour is more stable in the inner part of the train, while it slightly deviates in its head and tail. The standard deviation of the position for each bunch is comparable with the results achieved in single-bunch.

Changing the phase relation between the two input signals results in the same behavior observed in single bunch, with the performance getting slightly worse.

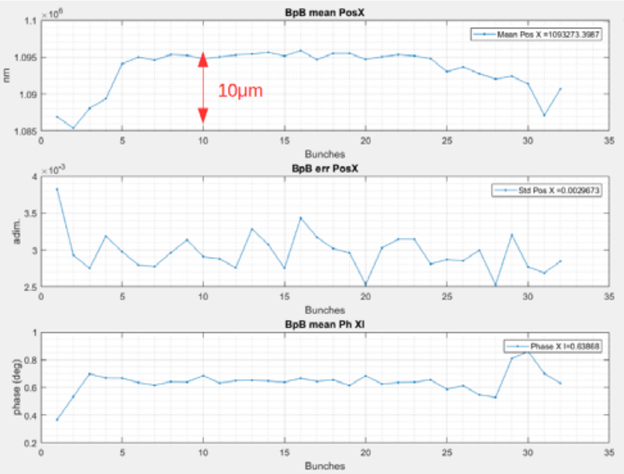

Figure 8: Performance in bunch train mode.

Linearity and Long-Term Stability

The measurements in this section were done to characterize the HW in terms of linearity and long-term stability. To judge the linearity of the system, one of the two input signals was progressively attenuated using an external attenuator, and the position was monitored through the instrument. Figure 9 presents the results of the measurements which show a good linearity.

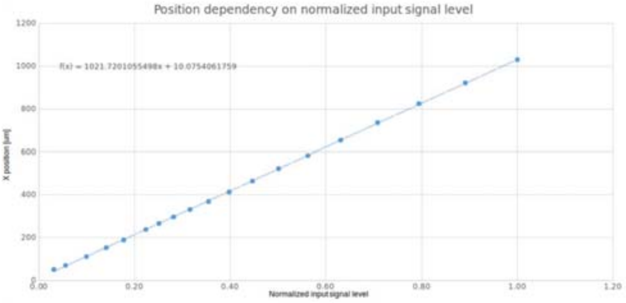

Figure 9: Linearity of the position calculation.

To evaluate the long-term stability, the setup was left running for 48 hours. The input signal was a train of bunches and the analisys focused on the measurements on the 10th bunch inside of the train. As it is possible to see from Figure 10, both input signals measure the changes in the signal levels due the environment condition deviations between day and night. As the position comes from the ration between the two amplitudes, this influences cancel out in the position, which remains within ±1µm, as it is visible in Figure 11.

The excellent long-term stability is also due to the method chosen to cool the instrument: the big heatsink, together with heat pipes provides uniform temperature conditions for the RF chains, which are therefore not exposed to gradients which would be visible in the position.

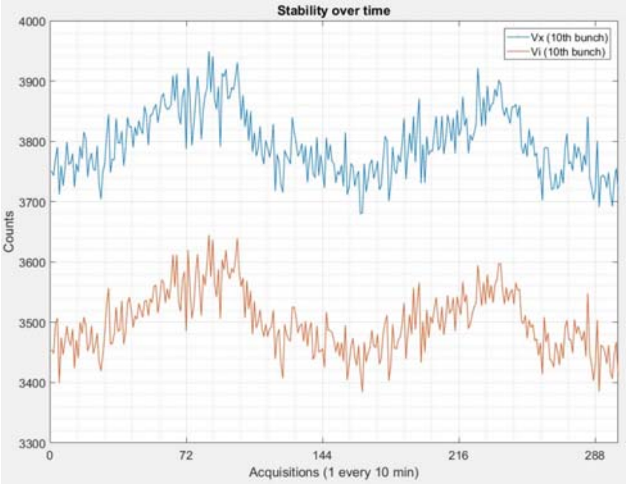

Figure 10: Long-term evaluation of signal amplitudes.

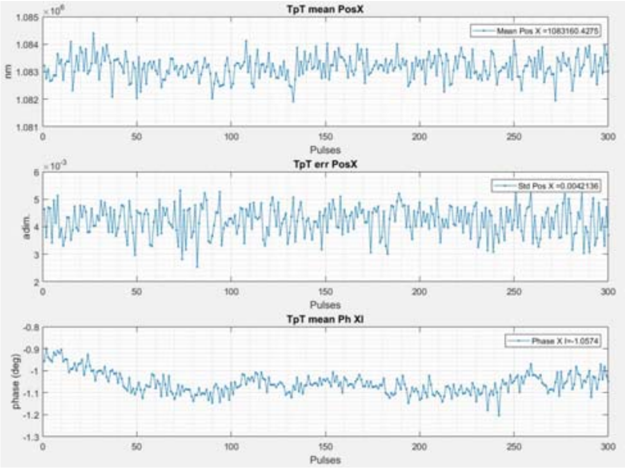

Figure 11: Long-term evaluation of position.

CONCLUSIONS

Based on simulations and extensive prototyping, the cavity BPM readout electronics for the ELI-NP GBS were developed into a commercial system. In order to fulfill the requirements of the project, the electronics employ 500MSps A/D converters and a novel approach for separating the bunches using deconvolution filters.

In order to evaluate the performance of the system in the laboratory, the people from INFN-LNF organized a test-setup able to generate test-signals which are a good approximation of the signals expected from the machine. The setup uses a pulse generator and the BPM16 cavity which will be installed in the accelerator.

The results from the measurements are in line with the expectations: despite of the non-ideal input signals the achieved RMS position resolution is within 5µm for a position range of ±1mm. The deconvolution filter concept has been validated with individual and multiple-bunch sequences. The long term stability and linearity are excellent.

Still there are some aspects to be understood, in particular the influence of the phase difference between the input channels on the position resolution. Measurements on the real machine will help to clarify this aspect.

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