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The Signal Processing Electronics for the Beam Position Monitors of Russian Fourth Generation Synchrotron Radiation Source[1]

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Abstract—The project of fourth-generation Ultimate Source for Synchrotron Radiation (USSR-4) is under development in Russia by leading of National Research Center "Kurchatov institute". Some of diagnostic systems required for the new facility have to be developed or redeveloped to satisfy the features of the new facility. Hundreds beam position monitors (BPM) are installed along beam transfer lines, booster and storage rings to control the electron beam position. In booster and storage ring the electronics of BPM has to provide both the normally beam circulation and the first beam turn operation. It has to provide beam position monitoring in the bunch-by-bunch option for all operational modes [1]. In this manuscript we discuss the architecture of the BPM electronics, important aspects of the analog front-end, available components and a resulting performance of designed electronic module.

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INTRODUCTION

Modern science demands comprehensive, powerful and accurate instrumentation. Physics of surfaces is one of well-known consumers of X-ray based instruments. These tasks could be rather exotic like interfaces study in soft matter [2].

The beam position monitors are most widely used system in electron synchrotrons. They provide a routine control of the conditions of the beam propagation in the accelerator or over the storage ring. Fourth generation synchrotrons demonstrate a new challenge for beam diagnostics and particularly for the beam position monitoring. To operate in low emittance mode and stay in diffraction limited status, the beam position monitors must be able to detect small orbit distortions due to the micrometer range misalignment of the magnet optics elements. Minimization of the beam emittance plays a main role in fourth generation synchrotron radiation sources. They use a comprehensive magnet optics minimizing non-linear effects in magnetic field. For sextuples magnets it is important to keep their magnetic axes exactly at the beam line. Therefore, appropriate beam position monitors should provide also *absolute* position measurement with high accuracy. Contemporary electronics allow increasing of the performance of analog and digital [3] signal processing. Presently synchrotron radiation laboratories upgrade their BPM electronics to meet new requirements [4].

The basic idea of a charged beam position measurement in accelerators is demonstrated in Fig. 1. The beam (in the center) moves in the direction from the reader. The beam is normally modulated and exist in the form of the train of short electron bunches. Generally, each bunch have its own position in the cross-section of the vacuum pipe. Bunch-by-bunch measurement mode distinguishing separated bunches allowing to avoid averaging of their positions over multiple items. The measurement electrodes have capacitive coupling to the beam and loaded by low-noise amplifiers having necessary sensitivity and frequency pass band.

Measured voltages, whatever it means, define the beam position by difference-over-the sum formula:

$$X_{\rm BPM} = K_x\left((U_1+U_4)-(U_2+U_3)\right)/\left((U_1+U_2+U_3+U_4\right),$$

$$Y_{\rm BPM} = K_y\left((U_1+U_2)-(U_3+U_4)\right)/\left((U_1+U_2+U_3+U_4\right),$$

where $X_{\rm BPM}$ is the x coordinate of beam center of mass in plane of BPM, $Y_{\rm BPM}$ is the y coordinate of beam center of mass in plane of BPM, U_1–U_4 are the measured signals from the BPM electrodes and K_x and K_y are the coefficient for x and y direction respectively. It works well as a zero-crossing detector when the BPM

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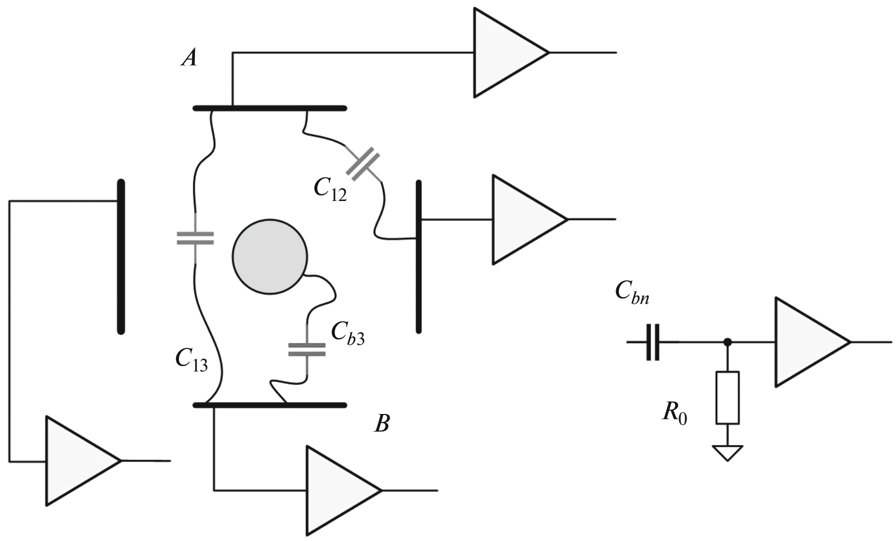

Fig. 1. Simplified diagram of the BPM front-end.

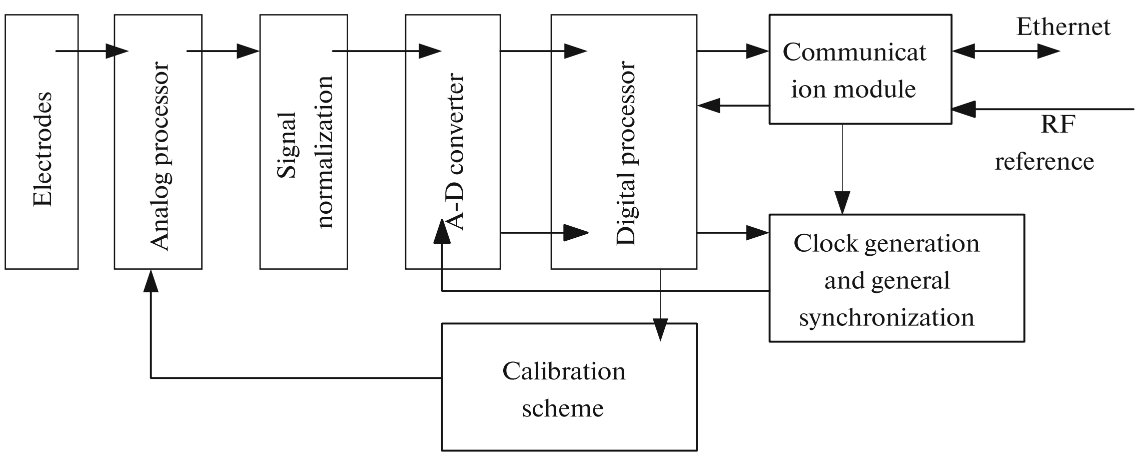

Fig. 2. Layout of the BPM electronics.

is correctly aligned to the magnetic axes of the nearest quadrupole or sextuples lens.

THE STRUCTURE OF A BPM STATION

The general structure of the BPM electronics is shown in Fig. 2. For simulation we used the signals from electrodes similar to ones described in [5]. The structure includes a signal processing unit, signal normalizing scheme, analog-to-digital converter and digital signal processor. There is also a high quality clock synthesizer, communication module and a calibration scheme.A latest trend in the beam position electronics is a maximal involving of a digital signal processing. As shown in Fig. 3 the analog part is simplified to reduce a production and maintenance cost of the device. It is much easy to achieve desired frequency response in a digital domain, where no non-linearity, no amplitude and phase distortions are over full dynamic and frequency range. Analog-to-digital converters (ADC), receives 'clean' signals from the electrodes. All necessary operations like filtering, deconvolution and position calculation perform in fast field-programmable gate arrays (FPGA). Only few operations like signal normalization and antialiasing filtering are necessary in the analog domain.

NOISE AND DRIFT OF PARAMETERS

There are some factors limiting the position measurement accuracy. The noise affects all kind of measurements by adding uncertainties to the measurement

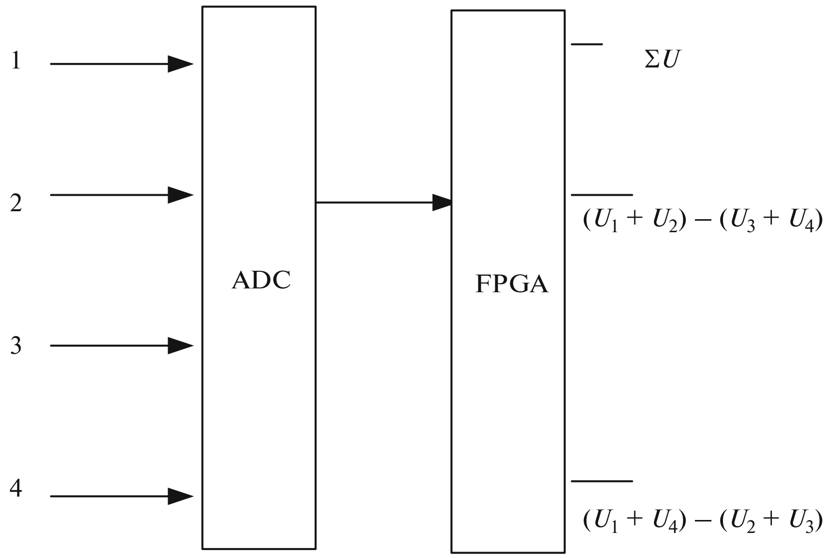

Fig. 3. A modern approach of the signal front-end.

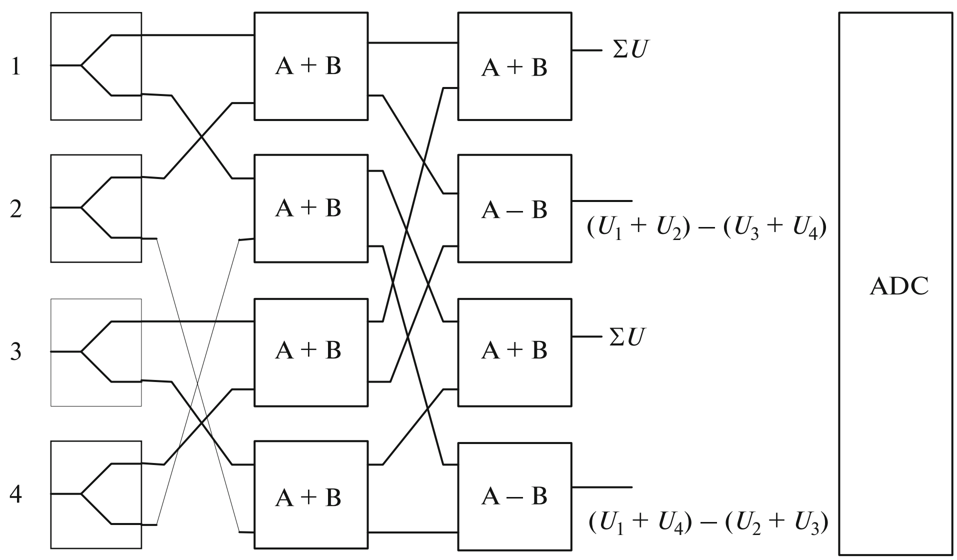

Fig. 4. BPM electronics use analog signal combiners.

results. Another factor is a drift, thermal or ageing, of transmission coefficient for analog amplifiers and ADCs. Drift is a common problem for low frequency measurements. In the case of BPMs, it could add an offset to the absolute position value and it is why the BPM for fourth generation synchrotron must preferably use analog signal combiners (see Fig. 4). Ithelps to solve both problems. First, analog combiners have a drift, which is in order of magnitude lower than amplifier and ADC have. Second, analog subtractor relatively reduces the multiplicative component of the ADC noise. Just look on following equations for the voltage difference.

$$\Delta U_D = \Delta U + 2^{1/2}\varepsilon_1 + 2^{1/2} FS\varepsilon_{\mathrm{ADC}},$$

$$M\Delta U_A = M(\Delta U + 2^{1/2}\varepsilon_1) + FS\varepsilon_{\mathrm{ADC}},$$

where one takes the voltage difference $\Delta U = U_1 - U_2$ either by digital ΔU_D, or by analog ΔU_A subtraction. The digital one is simple, linear and frequency independent but it introduces a noise $\varepsilon_{\mathrm{ADC}}$ which comes from the ADC in addition in addition to thermal noise of analog path ε_1. Usually $\varepsilon_{\mathrm{ADC}}$ is measured in decibels to the full scale (*FS*) of the ADC. It could be shown that this kind of noise is dominated in BPMs built in by scheme from Fig. 3. In their turn, the approach from Fig. 4 and analog subtractor electronics uses an

Table 1. Parameters of ADCs available at the market [3]

ADC	Resolution	SNR@300 MHz	Rate MSPS	No of channels	Cost per channel*	Analog BW
AD9680	14	65.3 dB	820	2	$185	2000
ADS54J20	12	67	1000	2	$195	1200
ADS5400	12	59	1000	1	$1080	2100
AD9208	14	60.2	3000	2	$663	9000

*, Recommended price in US.

analog amplification of the difference signal ΔU. M is an amplification factor, which is as large as it is necessary to match ΔU to the full scale of the ADC. Roughly, for the estimation let's assume that we measure the beam position in one-millimeter range near the axis of a 20 millimeters diameter aperture. Under such conditions, M could be set to 10 or a bit higher, so the relative contribution of the ADC noise reduces by 20 decibel or more.

ADC SELECTION

The ADC choice is critical for BPM performance. ADC parameters as well as the cost of ADC and supplemental components are important due to the large amount of BPM stations over the electron accelerator ring (several hundreds). Some parameters of ADCs, which are presently available at the market are given in Table 1 [6].

AD9680 looks like the most suitable for BPM electronics. It has 2 GHz bandwidth, high sampling rate and reasonable price. But even with such sampling frequency the ADC is not able to satisfy the Nyquist criteria known from sampling theory for bunch by bunch operation [7, 8].

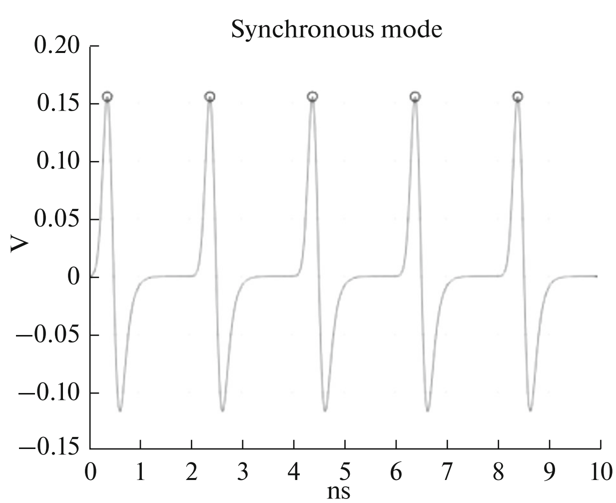

Fig. 5. Synchronous mode of ADC operation.

Actually the system should operate at half of Nyquist in synchronous mode as shown in Fig. 5. With such sampling rate and optimized signal chain we expect the performance of BPM improving by factor 10 or more in comparison to available commercial solutions.

SYSTEM SIMULATION

The corresponding model for simulation is given in figure 6. Layout includes current source I1 to simulate beam current. The beam displacement is simulated by the variation of coupling coefficient of the current-voltage convertor for model shown in details in Fig. 6 [9]. According to the beam displacement characteristics the beam displacement of 200 μm changes the signal in the channels for 5%. The model includes also equivalents for electrodes E1–E4. All other parts are elements for the signal treatment. Since signals from electrodes are used for vertical and horizontal coordinate measurements at the same moment, dividers SPL1–SPL4 split the power between horizontal and vertical measurers. In figure 6 only horizontal channel is shown in operation. Channels for vertical part are terminated by 50 Ohm resistor. Left and right signals are summarized by combiners SPL5 and SPL6. Resulted sums subtracted from each other giving the numerator for the beam position equation. The resulted signal has not the common part, therefore the variable part of the signal can be treated more accurate. Scheme in Fig. 6 was designed for signal to noise ratio estimation. The frequency response is simplified as it is described in the splitter/combiners chapter.

Radiofrequency broadband elements attenuate the signal making worst the signal to noise ratio. The noise power at the load is 0.9 nB/Hz$^{1/2}$ and amplitude of the signal for the beam displaced at 200 μm is 11.2 mV. The found RMS noise voltage is in range up to 2 GHz is 40 μV which corresponds to the 0.7 μm of the beam displacement. Such tolerance can be provided if the ADC noise would be remarkable lower in opposite to other discussed variants. To exclude the ADC noise, the signal has to be amplified in a such way that noise

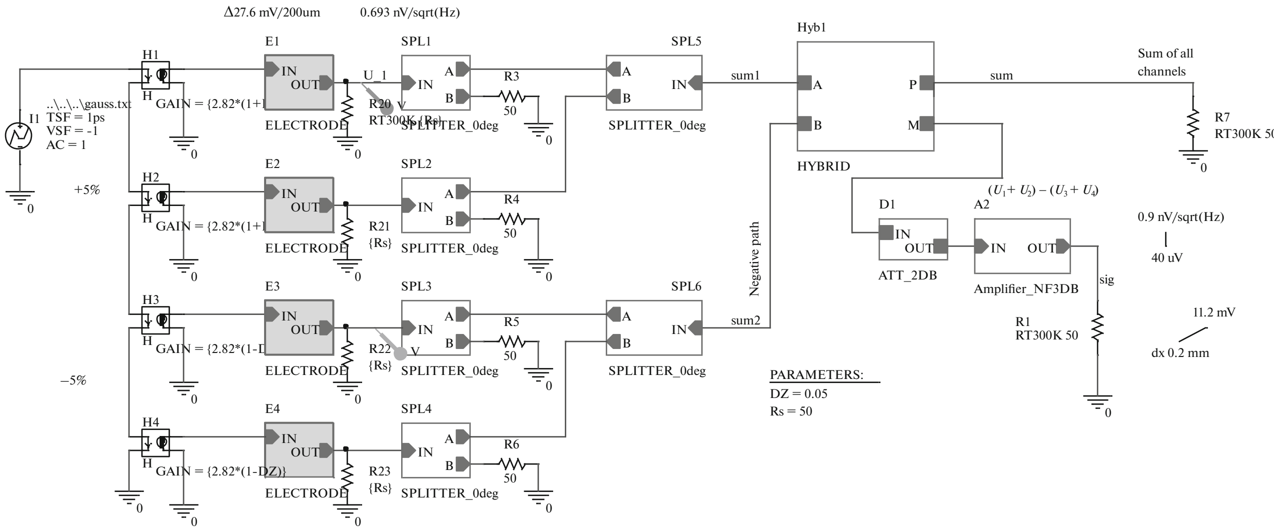

Fig. 6. Analog signal processor.

with amplitude 40 μV (−78 dBm) becomes higher for at least 3 dB than the ADC noise (−50 dBm). It means that it is enough to provide the amplification of 40 dB.

CONCLUSION

Beam position monitors are important part of the electron beam instrumentation in synchrotron radiation facilities. New generation of synchrotrons demands more accurate and fast responding positioning system for routine control and beam based alignment procedures. Beam position monitors for newly constructed accelerators need to be carefully designed to fulfill new demands and to use existing electronic components in optimal way. Presented model and correspondent equivalent scheme enable the analysis of the achievable parameters for the 4th generation light source BPM. As result the BPM performance with single-shot bunch-by-bunch geometrical beam position resolution at least ten times higher than commercial BPM can be provided. We estimate micrometer precision for beam position measurements for the single-shot bunch-by-bunch mode, and detection with submicrometer resolution of the electron beam betatron oscillations.

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