CONCEPT OF BEAM POSITION MONITOR WITH FREQUENCY MULTIPLEXING*

I. Pinayev[#], P. Cameron, BNL, Upton, NY 11793, U.S.A.

Abstract

Two most widely used beam position monitor (BPM) systems (manufactured by Bergoz [1] and Instrumentation Technologies [2]) implement switching technique to eliminate errors associated with drifts in the channel gains. High stability is achieved by an alternative routing of signals from all pick-up electrodes (PUE) through the same chain. Such an approach creates problems with turn-by-turn acquisition as well as measurement noise. In this paper, basing on the advances of digital signal processing that allow identical gains for the wide frequency ranges, we propose separating signals in the frequency domain. The experimental set-up and test results are presented. Practical realization of the beam position monitors is also discussed.

INTRODUCTION

Development of ultra-bright synchrotron radiation sources and high luminosity colliders requires unprecedented levels of beam stability. To achieve needed steadiness one can use a channel switching technique [1, 2] or utilize a pilot tone [3, 4]. The channel switching produces very low drifts but also manifests itself as narrow band measurement noise at the switching frequency. Another disadvantage is lack of the turn-by-turn (TbT) capabilities. Pilot tone technique can provide both stable long-term beam position monitoring and TbT data: however it requires extra hardware to be placed inside an accelerator tunnel.

In this paper we propose a new approach based on the separation of the signals from different pick-up electrodes (PUE) in the frequency domain combined with digital processing. Processing in the digital chain is a key element, because it provides stable and equal gain in the wide frequency range.

EXPERIMENTAL SETUP

The proposed signal processing scheme is shown in Fig. 1. For simplicity the scheme with two pick-up electrodes, A and B, is used (four-PUE implementation will be discussed later). Signal from each pick-up is divided into the two channels with equal amplitudes by splitters S_1 and S_2. Two local oscillators Osc 1 and Osc 2 set the intermediate frequencies (IF). Signals from each PUE are down-converted with mixers M_1-M_4 and cross combined with combiners C_1-C_2. The first analog-to-digital converter (ADC) processes signal A at the first intermediate frequency and signal B with the second IF; the second ADC processes signal A at the second IF and signal B with the first IF.

Due to symmetry of the processing chain the first-order errors from the splitters and combiners (such as inequality of division and summation) and the amplitude variations of the local oscillators are cancelled; only the second-order terms remain. For the analysis purpose the variation of mixers insertion losses are included into the corresponding errors in splitters and/or combiners.

Components characterization

The tests were performed utilizing a LeCroy WavePro 7300A digital oscilloscope, ZFSC-2-4-S+ splitters/combiners, ZX05-10-S+ mixers by Mini-Circuits, two N5181A RF signal generators by Agilent were used as local oscillators, and an RF and Clock Generator by Instrumentation Technologies for the signal source. The carrier frequency was suppressed by the low-pass filters with cut-off frequency depending on the chosen IF. The carrier frequency was set to 481.57 MHz to minimize the effect of reflected wave from the mixers.

First, the splitters and ADC were verified with two measurements in which signal after splitter goes directly and then is crossed to the two channels of the oscilloscope. The measured waveforms were fit with sine, and obtained amplitudes were used to calculate unevenness of the splitters and the gain inequalities of the ADCs. The channel gains were different by 6×10^{-3} and the splitter was found to have 1.4×10^{-3} unbalance.

Beam offset was simulated by insertion a 1 dB attenuator (theoretical transmission of 0.8913) into position A or position B. The measured transmission was 0.885.

Tests with Low IF

The initial measurements were performed with low IF, where the reduced sampling rate allows ADCs to have less noise and more effective bits. The local oscillators were set to 478.93 MHz (IF_1=2.64 MHz) and 478.01 MHz (IF_2=3.56 MHz). The SLP-5+ low-pass filters by Mini-Circuits have cut-off frequency of 5 MHz. The sequence of 10 µs duration was recorded with 1 Gs/sec rate. The recorded signals ware fitted with a two-tone sine waveform:

$$y = y_0 + A\cos\omega_1 t + B\sin\omega_1 t + + C\cos\omega_2 t + D\sin\omega_2 t \quad (1)$$

The obtained amplitudes were used to calculate the ratio of levels:

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[#]pinayev@bnl.gov

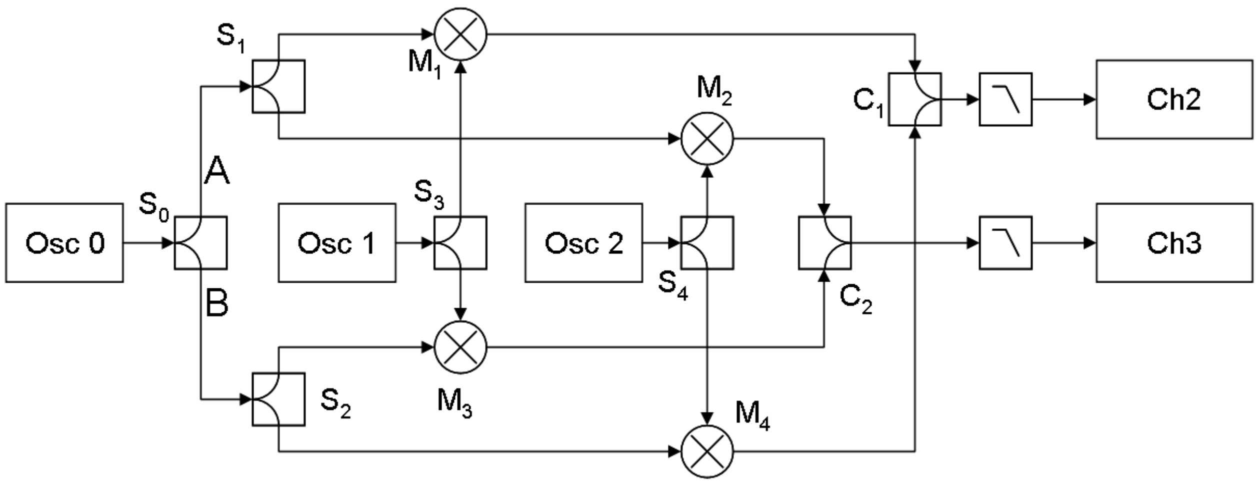

Figure 1: Test set-up for beam position monitor with frequency multiplexing.

$$R = \frac{\sqrt{A_2^2 + B_2^2} + \sqrt{C_3^2 + D_3^2}}{\sqrt{A_3^2 + B_3^2} + \sqrt{C_2^2 + D_2^2}} \qquad (2)$$

For the direct connection (without any attenuators) the ratio of the signals was R=1.0206±9.6×10^{-5}, with the attenuator in chain A 1.1467±1.8×10^{-4} and in chain B 0.9130±1.6×10^{-4}. Sensitivity to the ADC gain was verified by installation of another 1 dB attenuator before the Ch3 oscilloscope input. Direct measurements gave R=1.0195±1.1×10^{-4}; with attenuator in chain A R= 1.1457±1.7×10^{-4}.

The effect of local oscillator power variations was studied by varying Osc 2 amplitude. The obtained results are shown in Table 1.

Fig. 2 shows the observed ratio depending on the input signal level. During these measurements gain of the oscilloscope channels was adjusted accordingly. The legend shows the utilized scales. At low signal levels the ratio stays unchanged; when the mixers are overloaded the ratio changes substantially.

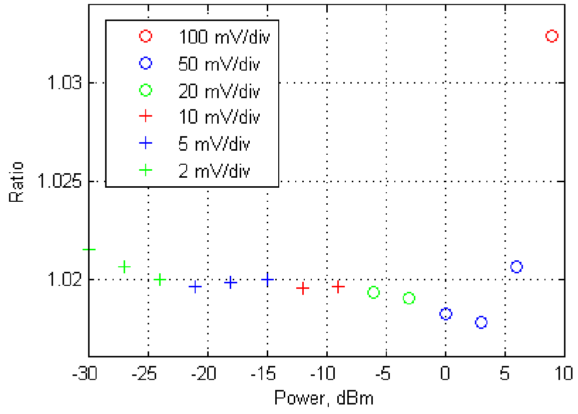

Figure 2: Dependence of measured ratio vs. Osc 0 power.

Table 1: Effect of local oscillator power for low IF

Osc 2 Power	R without attenuator	R with attenuator in position A
7 dBm	1.0232±1.6×10^{-4}	1.1488±2.0×10^{-4}
10 dBm	1.0204±1.8×10^{-4}	1.1470±1.7×10^{-4}
13 dBm	1.0164±1.4×10^{-4}	1.1437±1.3×10^{-4}

The storage rings usually operate with partial fill and spectrum of the beam signal has sidebands around RF frequency, which are separated by the revolution frequency F_{rev}. Fig. 2 shows spectrum of the signal for 80% fill with revolution frequency of the NSLS-II storage ring (378 kHz). The separation between two intermediate frequencies was chosen in such way that spectral content does not overlap.

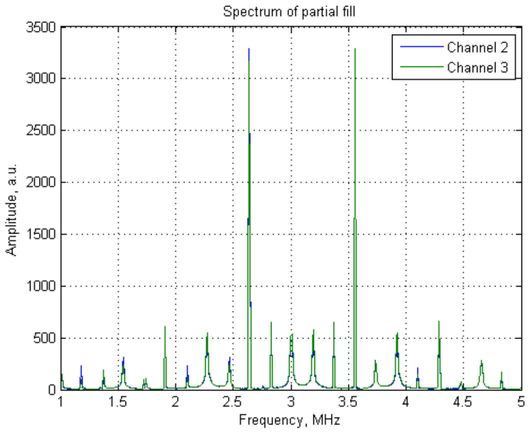

Figure 3: Spectrum of the beam with 80% partial fill.

For the reduction of the fill duty factor the main line decreases and sidebands amplitudes grows. In order to improve signal-to-noise ratio the energy in the sidebands should accounted as well. Therefore, to evaluate capabilities with TbT data the fit with N sidebands was utilized:

$$y = y_0 + \sum_{i=-N}^{N} A_i \cos[(\omega_1 + i\omega_{rev})t + \phi_i] + \sum_{i=-N}^{N} B_i \cos[(\omega_2 + i\omega_{rev})t + \varphi_i] \qquad (3)$$

Tests with High IF

In order to have TbT resolution, higher intermediate frequencies are required. For this purpose frequencies of local oscillators were set to 446.06 MHz and 451.41 MHz (IF_1= 35.51 MHz, IF_2=30.16 MHz). The low-pass filters used were SLP-50+ by Mini-Circuits with cut-off frequency of 48 MHz.

The tests similar to the ones done for low IF were performed. The results are shown in the Tables 2 and 3, and Figs. 3 and 4.

Table 2: Effect of ADC mismatch

Connection	R without attenuator	R with 1dB attenuator in Ch3
Direct	$1.0578\pm2.3\times10^{-4}$	$1.0583\pm4.1\times10^{-4}$
A	$1.1881\pm1.1\times10^{-4}$	$1.1889\pm3.5\times10^{-4}$
B	$0.9554\pm1.1\times10^{-4}$	$0.9472\pm2.2\times10^{-4}$

Table 3: Effect of local oscillator power for high IF

Osc 2 Power	Ratio with attenuator in position B
7 dBm	0.9491
8 dBm	0.9490
9 dBm	0.9477
10 dBm	0.9459
11 dBm	0.9434
12 dBm	0.9406
13 dBm	0.9382

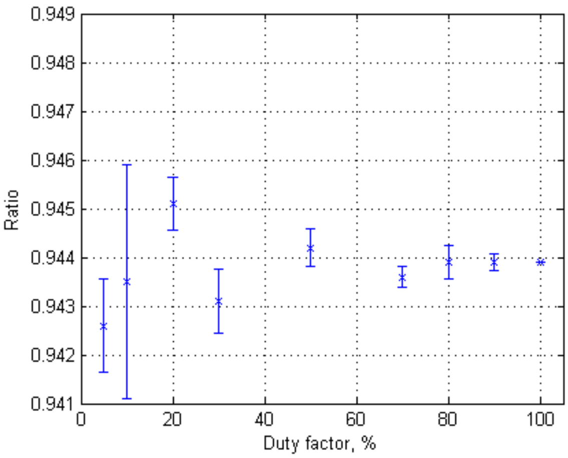

Figure 3: Turn-by-turn measurements with different fills.

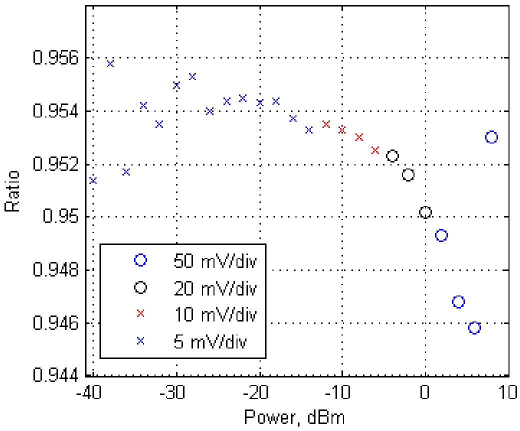

Figure 4: Ratio vs. signal level.

OTHER CONFIGURATIONS

A simpler configuration can be achieved when the frequency of one of the local oscillators is set to zero, i.e., no frequency conversion. A low-pass filter installed after a mixer can suppress the upper sideband as well as the carrier line. The amplitudes of the signals in both paths can be equalized with attenuators.

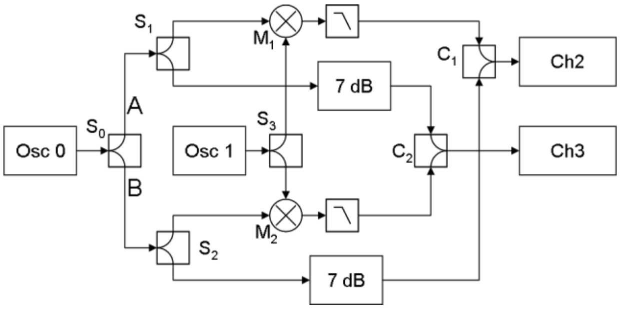

Figure 5: Layout of the signal processing chain with single local oscillator and two mixers.

It is possible to build a receiver without mixers by utilizing the higher harmonics of the beam signal. For example one channel will be used for the measurement of the 1st harmonic of signal form button A and second harmonic from button B, when the other channel will monitor 2nd harmonic from button A and the first harmonic from button B. The scheme can build using four diplexers as shown in Fig. 6.

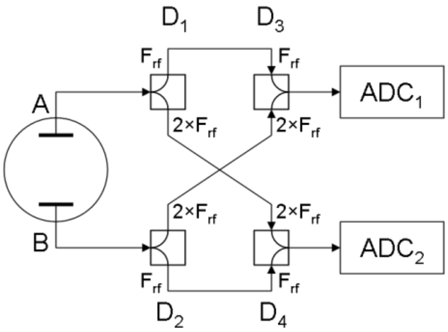

Figure 6: Set-up with four diplexers. The bandwidth of the system is defined by diplexers bandwidth.

FOUR PUE IMPLEMENTATION

In principle, the proposed set-up can be easily expanded for case of four pick-up electrodes. The signals should be split by four 4-way splitters, mixed into the four IF (four local oscillators required), combined and processed with four ADCs. More cumbersome but straightforward analysis similar to the two PUE case shows that all first order errors are suppressed as well.

But there is a possibility to utilize two double-channel devices connected to the diagonally located PUE (Fig. 7).

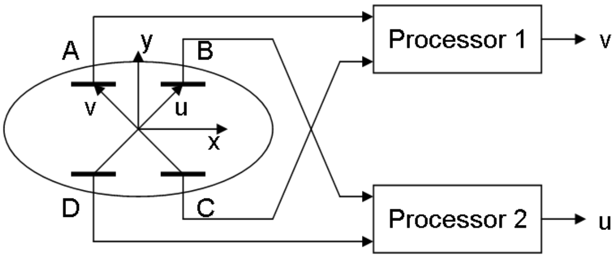

Figure 7: Usage of two receivers for 4 pick-up electrodes.

In this case two variables u and v are found and the beam position can be found by coordinate transformation:

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{bmatrix} a & -a \\ b & b \end{bmatrix} \begin{pmatrix} u \\ v \end{pmatrix} \tag{5}$$

CONCLUSIONS

Measurements confirmed the expected benefits of RF BPM with frequency multiplexing in the wide dynamic range:

- A 10% variation of ADC “gain” changes the observed ratio within error margins;
- Sensitivity to local oscillator power is most likely due to the changing impedance mismatch and circuit asymmetry (different length of cables);
- The device is capable of processing signals from a beam with a partial fill;
- The scheme used is capable of turn-by-turn measurements (more study is needed for low fill modes).

Four buttons signals can be processed, as well.

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