BROOKHAVEN NATIONAL LABORATORY

CONCEPT OF BEAM POSITION MONITOR WITH FREQUENCY MULTIPLEXING

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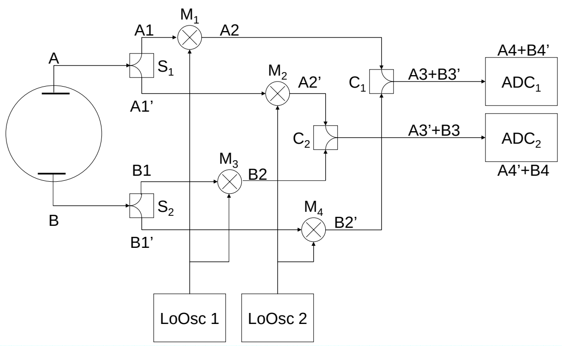
Abstract

Two most widely used beam position monitor (BPM) systems (manufactured by Bergoz and Instrumentation Technologies) 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 we propose a different approach with separating signals in the frequency domain, based on advances of digital signal processing that allow identical gains for the wide frequency range. The experimental set-up and results are presented. Practical realization of the beam position monitors is also discussed.



Proposed set-up

Signal from each pick-up is split 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 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 the variation of mixers insertion losses can be included into the corresponding errors in splitters and/or combiners.

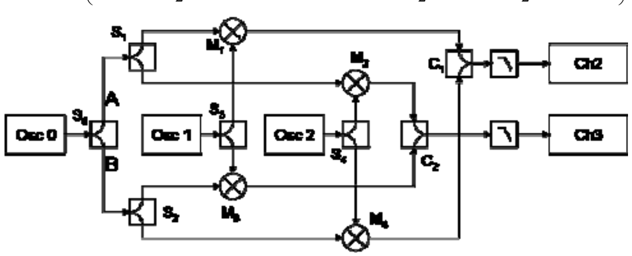
$$\text{Position } \Delta = k\frac{A_4 + A_4' - B_4 - B_4'}{A_4 + A_4' + B_4 + B'}$$

$$A_1 = 0.5A(1-\delta_{S1}) \quad A_1' = 0.5A(1+\delta_{S1})$$
$$B_1 = 0.5B(1-\delta_{S2}) \quad B_1' = 0.5B(1+\delta_{S2})$$
$$A_2 = A_1(1-\delta_{LO}) \quad A_2' = A_1'(1+\delta_{LO})$$
$$B_2 = A_1(1-\delta_{LO}) \quad B_2' = B_2'(1+\delta_{LO})$$
$$A_3 = A_2(1-\delta_{C1}) \quad A_3' = A_2'(1+\delta_{C2})$$
$$B_3 = B_2(1-\delta_{C2}) \quad B_3' = B_2'(1+\delta_{C1})$$
$$A_4 = A_3(1-\delta_{ADC}) \quad A_4' = A_3'(1+\delta_{ADC})$$
$$B_4 = B_3(1+\delta_{ADC}) \quad B_4' = B_3'(1-\delta_{ADC})$$

$$A_4 = 0.5A(1-\delta_{ADC})(1-\delta_{C1})(1-\delta_{LO})(1-\delta_{S1})$$
$$A_4' = 0.5A(1+\delta_{ADC})(1+\delta_{C2})(1+\delta_{LO})(1+\delta_{S1})$$
$$B_4 = 0.5B(1+\delta_{ADC})(1-\delta_{C2})(1-\delta_{LO})(1-\delta_{S2})$$
$$B_4' = 0.5B(1-\delta_{ADC})(1+\delta_{C1})(1+\delta_{LO})(1+\delta_{S2})$$

$$A_4 + A_4' \approx A\left(1+\delta_{ADC}\frac{\delta_{C1}+\delta_{C2}}{2} + \delta_{ADC}\delta_{LO} + \delta_{ADC}\delta_{S1} + \delta_{LO}\frac{\delta_{C1}+\delta_{C2}}{2} + \delta_{S1}\frac{\delta_{C1}+\delta_{C2}}{2} + \delta_{LO}\delta_{S1}\right)$$

$$B_4 + B_4' \approx B\left(1-\delta_{ADC}\frac{\delta_{C1}+\delta_{C2}}{2} - \delta_{ADC}\delta_{LO} + \delta_{ADC}\delta_{S2} + \delta_{LO}\frac{\delta_{C1}+\delta_{C2}}{2} + \delta_{S2}\frac{\delta_{C1}+\delta_{C2}}{2} + \delta_{LO}\delta_{S2}\right)$$

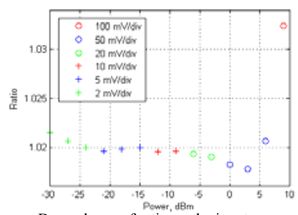


Test set-up

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 intermediate frequency.

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.



Dependence of ratio on the input power

Dependence of ratio on the LO power

Osc2 Power	R without attenuator	R with attenuator
7 dBm	$1.0232\pm1.6\times10^{-4}$	$1.1488\pm2.0\times10^{-4}$
10 dBm	$1.0204\pm1.8\times10^{-4}$	$1.1470\pm1.7\times10^{-4}$
13 dBm	$1.0164\pm1.4\times10^{-4}$	$1.1437\pm1.3\times10^{-4}$

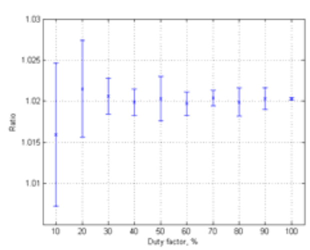
The initial measurements were performed with low IF, where the reduced sampling rate allows ADCs to have less noise and more effective bits. The local oscillators were set to 478.93 MHz (IF_1=2.64 MHz) and 478.01 MHz (IF_2=3.56 MHz). The SLP-5+ low-pass filters by Mini-Circuits have cut-off frequency 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:

$$y = y_0 + A\cos\omega_1 t + B\sin\omega_1 t + C\cos\omega_2 t + D\sin\omega_2 t$$

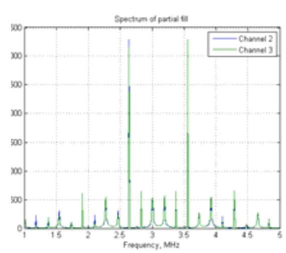
The obtained amplitudes were used to calculate the ratio of levels:

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

For the direct connection (without any attenuators) the ratio of the signals was R=$1.0206\pm9.6\times10^{-5}$, with the attenuator in chain A $1.1467\pm1.8\times10^{-4}$ and in chain B $0.9130\pm1.6\times10^{-4}$. Sensitivity to the ADC gain was verified by installation of another 1 dB attenuator before the Ch3 oscilloscope input. Direct measurements gave R=$1.0195\pm1.1\times10^{-4}$; with attenuator in chain A R= $1.1457\pm1.7\times10^{-4}$.



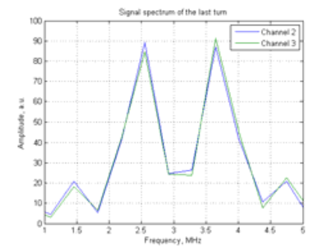
Fill pattern dependence

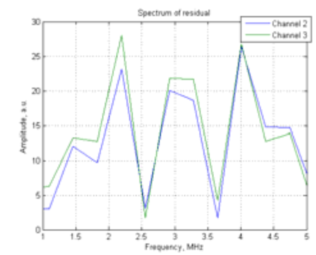


Spectrum of signal with 80% fill

Turn-by-turn Processing with Low Frequency IF

Fit $$u = u_{offset} + \sum_{i=-N}^{N}\left[A_i\cos(\varpi_{IF1} + i\varpi_{rev})t + B_i\sin(\varpi_{IF1} + i\varpi_{rev})t + C_i\cos(\varpi_{IF2} + i\varpi_{rev})t + D_i\sin(\varpi_{IF2} + i\varpi_{rev})t\right]$$





Processing was done with data from one "turn" not for full trace.

Sudden change in the ratio at 40% fill indicates that the sidebands start affect measurements of adjacent channel.

Increasing number of side lines does not help. We need to increase separation between IF_1 and IF_2.

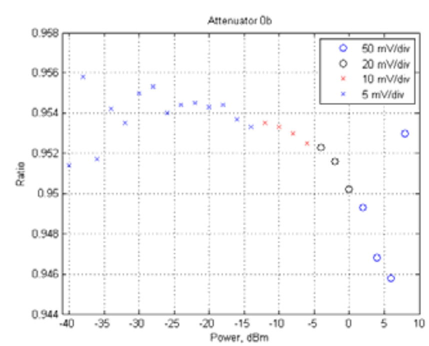
Fill	Ratio (Main + 1 side)
100%	1.0200±0.0054
90%	1.0307±0.0143
80%	1.0204±0.0111
70%	1.0272±0.0203
60%	1.0338±0.0144
50%	1.0306±0.0199
40%	1.0524±0.0437
30%	1.0088±0.0296
20%	1.0060±0.0617
10%	1.0088±0.0771

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.

1 dB Attenuator	Direct connection to Ch3	Ch3 with 1 dB attenuator
None	$1.0578\pm2.3\times10^{-4}$	$1.0583\pm4.1\times10^{-4}$
Position A	$1.1881\pm4.8\times10^{-4}$	$1.1889\pm3.5\times10^{-4}$
Position B	$0.9554\pm2.5\times10^{-4}$	$0.9472\pm2.2\times10^{-4}$

Dependence of ratio on the LO power

LO2 power	Ratio with attenuator
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



Dependence of ratio on the input power