Beam Position Signal Processing

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Abstract

Rf signal processing techniques for BPM are discussed, including some aspects on the characteristics of the beam position pick-up. The methods are suitable for single-bunch/single-pass applications, as well as for multi-bunch/multi-turn average position measurements.

1 INTRODUCTION

The beam position signal processing consists of a set of electronics which interfaces the analog signal supplied by the beam position pick-up with the data acquisition of the control system. Its task is to extract from the signals, supplied by the pick-up electrodes the horizontal or vertical beam displacement with respect to the center of the vacuum chamber. Thus ensues the *beam position measurement*. The main goal is an intensity independent position measurement with maximum resolution over a wide range of beam currents.

The methods discussed require bunched particle beams, which excite signals with significant levels in the rf-range in the passed through position pick-up. The resulting position information, delivered by the rf-signal processing electronics, is an analog output signal which stays constant ("quasi"-DC) for a specified time. This *measurement* time varies with application (single bunch/pass position measurement, averaging over a specified number of turns/bunches) and accelerator conditions (minimum/maximum bunch-to-bunch distance, ω_{rev}, etc.). As many control systems prefer to get their data in a digital format, digitalization and data buffering of the output signal have to follow (not part of this report).

2 PICK-UP CHARACTERISTIC

Before discussing the rf signal processing techniques in detail it is worth having a rough idea about the signals to be analysed.

The position pick-up is a vacuum device acting on the electromagnetic field of the passing bunch. It's electrodes are usually arranged symmetrically in order to obtain a position measurement with respect to the beam pipe's center, as well as to separate the horizontal and vertical axes. For our applications two pick-up quantities are important:

2.1 Transfer Function

The transfer function characterizes the coupling between one pick-up electrode and a single bunch passing the pick-up in it's center. It can be written as transfer impedance:

$$Z_{electr.}(\omega, \rho) = \frac{v_{electr.}(\omega, \rho)}{i_{bunch}(\omega) \cdot k_{bunch-electr.}(\rho)} \quad (1)$$

and is the frequency-domain equivalent to the impulse response $h_{electr.}(t, \tau, \rho)$ of the pick-up in the time-domain. The frequency independent factor k takes the beam-electrode coupling due to the transverse particle distribution ρ into account (needs to be known only roughly). Together with the single bunch current[1] we get the pick-up electrodes output voltage $v_{electr.}(\omega, \rho)$. This has to be a signal in the rf-range in order to be processed by the techniques discussed here, i.e. ω in $v_{electr.}(\omega)/v_{electr.,max} \gtrsim 1/\sqrt{2}$ are radio frequencies. For a single-bunch/single-pass processing, a broadband spectrum is further required, whose time domain signal $v_{electr.}(t)$, as an inverse frequency transformation (Fourier, Laplace) of $v_{electr.}(\omega)$, is short (in time) compared to the systems measurement time (or minimum bunch-to-bunch time distance).

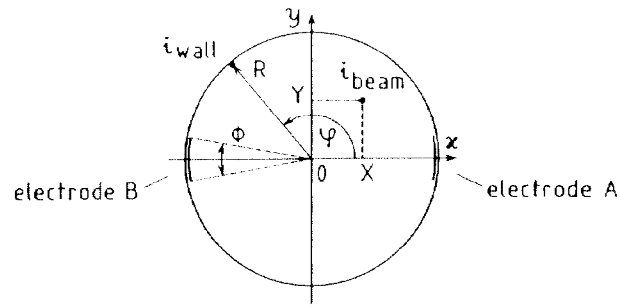

Figure 1: Simplified horizontal position pick-up

2.2 Position characteristic

For the estimation of the pick-up's position characteristic, all high frequency effects and other imperfections (skin effect, surface roughness, etc.) are negelected. The electrodes are taken as infinitly thin isolated surfaces on the beam pipe (negelecting their particular structure). Furthermore we limit ourselves to a circular cylindrical vacuum chamber passed through by an infinitly small coasting beam[2] (Figure 1). [2] applies the method of conformal mapping to this electrostatic problem and gives the wall

[1] $i_{bunch}(\omega) = I_{beam,DC} \exp[-\frac{(\sigma\omega)^2}{2\beta c}]$ for gaussian longitudinal particle distributions.

[2] A finite uniform round beam [1] will give the same results, as long as its radius is small comparared with the beam pipes radius: $r \ll R$.

current

$$i_{wall}(\varphi) = -\frac{i_{beam}}{2\pi}\frac{1-x^2-y^2}{1+x^2+y^2-2x\cos\varphi-2\sin\varphi}$$

at the position φ on the vacuum chamber surface[3] R as result, where $(x = \frac{X}{R}, y = \frac{Y}{R})$ is the normalized beam position. A pick-up electrode integrates i_{wall} over its width $W = \phi R$

$$i_{electr.,A} = -\frac{i_{beam}}{2}[F(x,y,\phi) - F(x,y,-\phi)]$$

$$\text{with: } F(x,y,\phi) = \arctan\frac{[(1+x)^2+y^2]\tan\frac{\phi}{4}-2y}{1-x^2-y^2}$$

The signal ratio[4]

$$\frac{A}{B} = \frac{F(x,y,\phi)-F(x,y,-\phi)}{F(-x,y,\phi)-F(-x,y,-\phi)} \tag{2}$$

of two adjacent, symmetrically arranged electrodes A and B of a horizontally[5] sensitive pick-up has to be formed in the signal processing electronics to allow a beam intensity independent position measurement. With restrictions to beam displacements around the pick-up center ($x_{max}^2 + y_{max}^2 \lesssim 0.25$) and electrodes of maximum width ($\phi_{max} < \pi/4$) eq. (2) simplifies to the compact approximation

$$\frac{A}{B} \approx \left(\frac{1+x}{1-x}\right)^2 \tag{3}$$

which is independent of vertical beam displacement and electrode width. From this we estimate the normalized sensitivity of a beam position pick-up to $d\frac{A}{B}/dx \approx 4$ at its center ($x = 0$).

3 RF-SIGNAL PROCESSING METHODS FOR BPM

The signal processing electronics has to create the signal ratio (2) or (3) of the two adjacent pick-up electrodes A and B, where each electrode generates a broadband signal $v_{electr.}$ due to (1). It is sufficient to analyse the measurement principles by exciting the electronics with a single frequency (CW operation).

3.1 Directional Coupler

Basic component is the directional coupler [4]. A symmetric, single-element coupler is formed out of two electromagnetically coupled, ideal (lossless, dispersionsless) transmission-lines. The transfer functions between the 4 ports are

signal into port A	transfer function	signal into port B
$\frac{v_B}{v_A}$ =	0	= $\frac{v_A}{v_B}$
$\frac{v_C}{v_A}$ =	$\frac{jk\sin\theta}{\sqrt{1-k^2}\cos\theta+j\sin\theta}$	= $\frac{v_D}{v_B}$
$\frac{v_D}{v_A}$ =	$\frac{\sqrt{1-k^2}}{\sqrt{1-k^2}\cos\theta+j\sin\theta}$	= $\frac{v_C}{v_B}$

In our applications the coupling coefficient k is set to 3 dB ($k = 1/\sqrt{2}$) and the couplers electrical length $\theta = 2\pi l/\lambda$ is matched to the electronics *operational* frequency (center-frequency $\omega_0 = \pi v/2l \equiv \theta = \pi/2$) [6]. Ports A and B are used as inputs, C and D as output ports.

Supplying the signals $v_A = A\exp(j\omega_0 t)$ and $v_B = B\exp(j\omega_0 t)$ into the A and B inputs and superposition of the corresponding transfer functions results in

$$\begin{aligned} v_{\tilde{C}} &= Ke^{j[\omega_0 t-(\varphi+\frac{\pi}{2})]} \\ v_D &= Ke^{j[\omega_0 t-(\varphi-\frac{\pi}{2})]} \end{aligned}$$

with $K = \sqrt{(A^2+B^2)/2}$ and $\varphi = \text{arccot}\frac{A}{B}$. In this configuration the directional coupler acts as an ***amplitude ratio-to-phase difference (A-P) converter***, because the phase difference

$$\psi_{\tilde{C}\text{-D}} = -2\text{arccot}\frac{A}{B} \tag{4}$$

between the output ports $\tilde{C}$ and D is a function of the signal-level ratio at the A and B inputs. For reasons of "matching" with the phase comparator[7], the couplers output port C is "delayed" by a transmission-line of same electrical length $\theta = \pi/2$ to a new port called $\tilde{C}$.

Delaying one of the two input signals v_A or v_B by 90^0 (done with a transmission-line of length $\theta = \pi/2$ between port B to the new input port $\tilde{B}$) causes an addition resp. subtraction of their amplitudes:

$$\Delta = v_{\tilde{C}} = \frac{A-B}{\sqrt{2}}e^{j(\omega_0 t-\frac{\pi}{2})} \tag{5}$$

$$\Sigma = v_D = \frac{A+B}{\sqrt{2}}e^{j(\omega_0 t-\frac{\pi}{2})} \tag{6}$$

In this "Power Summer" configuration[8] the coupler's C port is again $\frac{\pi}{2}$-delayed, so that the output signal's $v_{\tilde{C}} = \Delta$ and $v_D = \Sigma$ are in phase.

3.2 Basic Signal Processing Method

This technique is used in many accelerators for beam position monitoring [5,6, ...]. The pick-up output signals A and B of the two adjacent electrodes are connected via a directional coupler acting as an A-P converter. Its phase sensitive outputs are followed by the zero crossing detectors and ends in a phase comparator circuit (Figure 2).

The detectors limit the converter's output signal to a constant amplitude, and thus realize a ***beam intensity independent*** position measurement ($K = \sqrt{(A^2+B^2)/2} \sim i_{beam}$ or i_{bunch}). Over a large (*dynamic*) range of K they turn the sinewave signals into rectangular ("logic-level") signals with edges set at $t = (n\pi \pm \varphi)/\omega_0$. In this way, modified $\tilde{C}$- and D-branch signals are mixed in the phase comparator to a rectangular signal of $T = 1/2\omega_0$, whose pulsewidth is modulated by their time difference

[3] Results for beam pipes with different cross section (elliptical, rectangular, etc.) are available.

[4] There is some sign trouble in the same equation given in [3]. Sorry!

[5] All equations are given for the horizontal case., For vertical position measurement rotate the coordinate system by $\pi/2$

[6] These couplers are often called 90^0- or quadrature-hybrids

[7] see section "Basic Signal Processing Method"

[8] sometimes called 180^0-hybrid

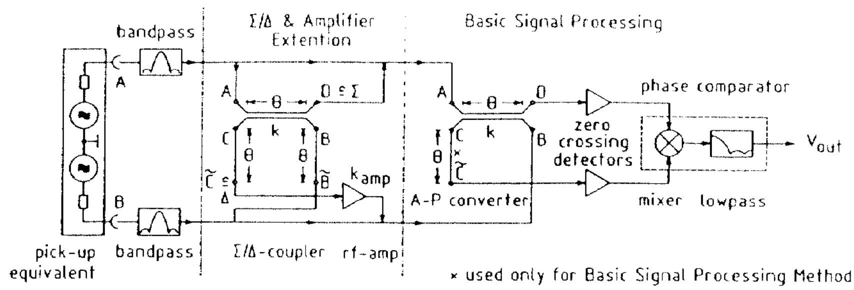

Figure 2: Block diagram of the rf-signal processing methods

$t_{\tilde{C}\text{-D}} = \psi_{\tilde{C}\text{-D}}/2\omega_0$. The low-pass circuit filters out the DC-component (avarage), which is proportional to $\psi_{\tilde{C}\text{-D}}$:

$$v_{out} = k_{mix}\psi_{\tilde{C}\text{-D}} \tag{7}$$

The phase comparator's *transfer* characteristic k_{mix} is rather linear for "digital" mixers (EXOR gates) but may be nonlinear for double balance diode mixers.

Combining (4) and (7) leads to the position characteristic

$$v_{out} = -2k_{mix}\operatorname{arccot}(\frac{A}{B}) \tag{8}$$

Using the approximation (3) for the pick-up's signal ratio characteristic $\frac{A}{B}$ in (8), gives an estimation of the normalized sensitivity[9]

$$\frac{dv_{out}}{dx} \approx 4k_{mix}k_{amp}\frac{1-x^2}{1+2x^2(1+2k_{amp}^2)+x^4} \tag{9}$$

Adding amplification at the output increases the sensitivity but not the effective position resolution, which is mainly limited by the noise produced in the input stage of the zero-crossing detectors.

3.3 "Modified" Signal Processing Method

In order to overcome this noise limitation caused by the ultra-broadband components[10] (zero crossing detectors and mixer) the *argument* of the arccot in (8) is "amplified":

$$v_{out} = k_{mix}(\frac{\pi}{2} - 2\operatorname{arccot}(k_{amp}\frac{\frac{A}{B}-1}{\frac{A}{B}+1}) \tag{10}$$

This is realized by extending the previous basic signal processing set up[11] with a Σ/Δ-Power-Summer arrangement at the inputs (Figure 2). The signals of the Δ-branch are amplified by a small-bandwidth, low noise rf-amplifier k_{amp} (its phase delay has to be compensated in the Σ-branch). Increasing the systems sensitivity (9) with amplification $k_{amp} > 1$ results in a $\psi_{\tilde{C}\text{-D}}$-range up to 360^0 (for the total range of beam position displacements $-1 \leq x \leq +1$). For technical and "linearity" reasons it should be limited to 180^0, which shrinks the beam diplacement range to $|x| \lesssim 1/2k_{amp}$ for $k_{amp} > 2$, assuming

$$v_{out} \approx k_{mix}[\frac{\pi}{2} - 2\operatorname{arccot}(2k_{amp}x)] \tag{11}$$

as the estimated overall position characteric. This reserves this processing method for the observation of small beam position displacements. The sensible range in the pick-up center may be changed by unbalancing the A or B input branch with attenuators.

3.4 Bandwidth Requirements

The CW single frequency operation treated up to now is equivalent to an average position measurement over many turns/bunches in a ring accelerator. It is realized by inserting a matched pair of bandpass filters between pick-up and processing electronics. They have to filter out a single harmonic line $\omega_0 = n\omega_{rev}$ (including sidebands) from the beam's picked-up frequency spectrum. The phase comparators lowpass has to supress all $2m\omega_0$-components arising in the mixer, its decay time should be similar to that of the bandpass filters. Together they specify the measurement time.

For single-bunch/-pass applications the filter characteristics need to be optimized in frequency- *and* time-domain. Their response has to realize quasi CW-conditions during the measurement interval, but should decay after as fast as possible – energy free – before the next bunch to be measured "enters". Some details on this subject are found in [3], resp. has to be published.

4 REFERENCES

[1] E. Regenstreif; CERN/PS/DL/76-2

[2] J. Borer and R. Jung; CERN/LEP-BI/84-14

[3] A. Jacob et al,DESY HERA 90-11

[4] Mattthaei, Young, Jones; *Micrawave Filters, Impedance-Matching Networks and Coupling Structures*

[5] S.P. Jachim et al; IEEE Trans. Nucl. Sci., NS-28,No. 3 (1981) 2323

[6] J. Bosser,L. Burnod, G. Ferioli; CERN/SPS/ABM/83-01/0058G

[9] Set $k_{amp} = 1$.

[10] The wide bandwidth is needed to achieve a satisfactory phase measurement over a large range of beam intensity.

[11] The $\frac{\pi}{2}$-delayline at the coupler's port C is taken out.