LOW-LATENCY HIGH-RESOLUTION SINGLE-SHOT BEAM POSITION MONITORS

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Abstract

In this paper design aspects of fast high-resolution, single-shot transverse beam position monitors (BPMs) are discussed. The focus is on BPMs which can provide (sub-) micrometer position resolution within measurement speeds of less than one hundred nanoseconds. Different pickups and analog signal conditioning electronics are reviewed. Their characteristics and limitations with respect to application in high-resolution, fast BPMs are pointed out. Exemplary implementations of pickups and electronics are reviewed. A BPM based on a resonant stripline pickup, developed for a fast transverse feedback system for the European X-FEL, is also presented.

INTRODUCTION

Next generation machines like the European X-Ray Free Electron Laser (E-XFEL) or the International Linear Collider (ILC) require extremely stable beams throughout their Linacs, in order to meet the transverse position stability requirements inside the undulators or at the interaction point, respectively. Table 1 lists the specified beam parameters [1][2].

Table 1: *Beam parameters of next generation machines.*

Parameter	E-XFEL	ILC
Energy	20 GeV	1 TeV
Bunch charge	1 nC	3.2 nC
Bunch spacing	200 ns	307 ns
Pulse length	3250	2820
Pulse rate	10 Hz	5 Hz
Bunch length σ_z	0.02 mm	0.3 mm
Bunch size σ_x	30 µm	554 nm
Bunch size σ_y	30 µm	3.5 nm

To stabilize the beam in the E-XFEL within 10 % of the ~30 µm beam size inside the undulators, a feedback system as shown in Figure 1 is currently under development at PSI and DESY [1]. In contrast to other proposed linac-based FELs that use single bunches with repetition rates in the order of 100 Hz, the E-XFEL will have bunch trains of up to 3250 bunches with 200 ns bunch spacing and 10 Hz repetition rate.

To damp harmful transversal beam position perturbations of these bunch trains up to hundreds of kilohertz (which originate from various noise sources and wakefields), the feedback system must act on a bunch-by-bunch basis. This requires beam position monitors (BPMs) having a position resolution in the micrometer region and very low latency.

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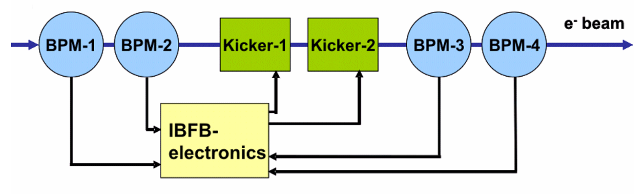

Figure 1: *Proposed topology of the E-XFEL intra-bunch-train feedback system [1].*

This paper focuses on fast BPMs for application in fast transversal intra-bunch-train feedback or interaction point feedback systems. Characteristic for such systems are the following parameters:

- Measurement rate: Equal to the bunch rate
- Bunch spacing: In the order of a few 100 ns
- Transversal resolution: ~1 µm
- Transversal measurement range: ~ ±1 mm
- Latency: <100 ns
- Bunch charge: 0.1 to 5 nC

Latency is the delay between the instant where the electron bunch passes through the pickup until the BPM outputs valid position data. Reasons for low latency are a) support of short bunch spacing, b) fast feedback.

Note that BPM systems for machines with longer bunch spacing (e.g. single-bunch Linacs) allow for much higher latency and therefore have relaxed requirements on noise, bandwidth, and processing speed. The construction of a such slow BPM may be entirely different from that of a fast BPM and therefore is not considered herein.

COMPONENTS OF A HIGH-RESOLUTION BPM

The building blocks of a BPM system are depicted in Figure 2. The pickup provides electrical signals that contain information about the beam position, usually in the signal amplitude. The most widely used pickup types include the button, matched stripline, resonant stripline, and cavity pickups.

Considering that, except for cavity pickups, the signal amplitudes from opposing pickup electrodes change by roughly 2 dB/mm when the beam moves in the respective plane, achieving micrometer resolution requires very careful signal handling: A change in cable attenuation of just 0.01 dB, which easily occurs when bending a cable, may lead to a measurement error of ~5 µm. Phase changes have similarly strong effects, depending on the processing scheme. Analog preprocessing close to the pickup is therefore necessary to transform the signals such that they can be transmitted over longer cables without the degrading effect on stability just described. This is done typically by some kind of normalization circuit or 180° hybrids (see below). In the case of a cavity pickup, the intensity or monopole mode signal may be rejected by special couplers or a 180° hybrid.

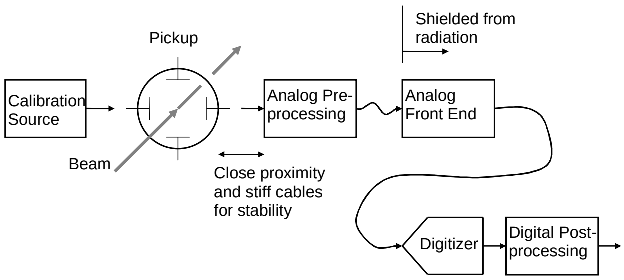

Figure 2: *Components of a BPM system.*

The analog front end may be favorably placed further away from the pickup in a radiation free location. However, cable length should be limited for low latency (1 m of standard cable makes a delay of 5 ns) and to reduce interference. Functions of the analog front end may include filtering, amplification, frequency conversion, normalization and detection. Afterwards the signal can be digitized for digital postprocessing, which may include offset and gain correction, linearization, normalization and filtering.

To compensate for drift and aging, the whole signal chain needs to be calibrated periodically. As a test signal either the beam (beam based alignment) or an electrical calibration signal source is used. It is possible to calibrate the BPM electrically between bunch trains.

PICKUP SELECTION

General Considerations

The type of pickup not only affects the achievable beam position resolution, but also many other characteristics of a BPM system, as well as the required signal processing. Some criteria for pickup selection are:

- Sensitivity of pickup signals to bunch charge and beam position (V/nC/mm)
- Operating frequency and bandwidth
- Separation of intensity and position signals
- Accuracy and stability
- Sensitivity to secondary beam parameters such as bunch length, beam angle, temperature
- Wakefields
- Size
- Manufacturability (complexity, tolerances, alignment)

The sensitivity of the pickup signals to beam position increases as the beam pipe diameter is made smaller. However, reasons for maintaining a large beam pipe diameter are a) vacuum pumping restrictions, b) reduced wakefield excitation and their effects on the beam, and c) easier initial machine alignment.

For achieving high resolution, we want high signal level and sensitivity. For low latency, we want high bandwidth. Both can be achieved with a resonant type of pickup operating in the gigahertz range, such as a short resonant stripline or a cavity pickup. A resonant stripline operating in the 1 to 3 GHz range or a cavity somewhere between 4 to 12 GHz will also be very compact.

To avoid overlap of signals produced by consecutive bunches, the quality factor (Q) of resonant pickups must be limited (i.e. to reduce ringing decay time).

Frequency and Bandwidth Selection

- The minimum signal bandwidth depends on the required latency and decay time
- Relative bandwidth decreases for higher operating frequencies (better for analog preprocessing)
- Electronics is more challenging to construct for higher operating frequencies
- Stay away from the machine RF and harmonics thereof
- Avoid widely used communication frequencies (e.g. GSM, DECT, WLAN)
- Measure other interferers in situ. Interference can enter the BPM system at the pickup and through long cables.
- Stay below beam pipe cutoff

PICKUP TYPES

Only commonly known pickups that provide signals strong enough for high-resolution BPMs are discussed. The signals produced by the widely used button pickups are too weak to obtain micrometer resolution for single-shot operation. There are also other special types of pickups recently developed, such as the perpendicularly mounted stripline pickup [3] or the inductive pickup [4], which are not considered here. Higher order modes (HOMs) of accelerating cavities have too large Q-factors and poorly defined dipole mode polarizations.

Matched Stripline Pickup

This pickup provides just sufficiently high signal level. Theoretical analysis shows that in the thermal noise limited case, it can provide submicrometer resolution. However, no practical implementation could be found which achieves this. A special feature of this pickup is its inherent directivity, allowing to separate counterpropagating beams. The electrical center depends on electrode alignment, and thus is rather poorly defined.

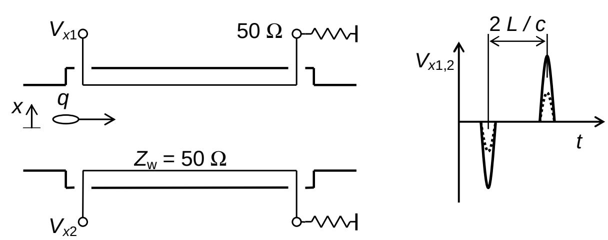

Figure 3: *Matched stripline pickup and waveform.*

A schematic sketch of the matched stripline pickup, along with its output voltage waveform, is shown in Figure 3. In the typical case the dielectric of the striplines is vacuum, the stripline characteristic wave impedance is chosen equal to the load impedance (i.e. 50 Ω), and coupling between stripline electrodes is weak. Under these conditions, each stripline electrode produces two pulses of opposite sign, separated by twice the propagation delay along the stripline. The ratio of the signal voltages $V_{x1,2}$ from opposing electrodes depends on the transversal beam position x. An estimate for the beam position is:

$$x \sim \frac{\Delta}{\Sigma} \quad \text{with} \quad \Delta = \left(V_{x2} - V_{x1}\right) \quad \text{and} \quad \Sigma = \left(V_{x2} + V_{x1}\right)$$

Around the center position, the difference signal is proportional to the beam charge and position ($\Delta \sim q\,x$), and the sum signal is proportional to the charge only ($\Sigma \sim q$). Alternatively, the log ratio of the levels of signals from opposing electrodes may be used as a position estimate, i.e. $x \sim \log(V_{x2} / V_{x1})$.

A BPM system utilizing a matched stripline pickup in a 34 mm diameter beam pipe has been presented in [5]. Using electronics based on the wide band time normalizer principle, a single-shot resolution of ~7 µm over ±5 mm range has been demonstrated at a bunch charge of 1 nC.

Resonant Stripline Pickup

Larger signal level within reduced bandwidth compared to matched striplines is obtained with resonant striplines [1][6]. As the signal level increases by the loaded quality factor Q_L, and the processing bandwidth is reduced by the same factor to match the pickups bandwidth, an improvement in resolution δx in the order of $\sim 1/Q_L$ can be achieved.

A schematic sketch of a resonant stripline pickup is shown in Figure 4. The 1.6 GHz pickup presented in [1] employs a simple and compact construction. All four electrodes (two per plane) are milled out of the same piece. The pickup exhibits a Q_L of 32, resulting in a time constant of 7 ns. Figure 4 shows its signal waveform, after low pass filtering to remove higher order harmonics.

Due to the strong coupling between stripline electrodes, the Δ-signal (dipole mode) and the Σ-signal (monopole mode) have slightly different resonance frequencies. For the pickup described above, the separation is 25 MHz.

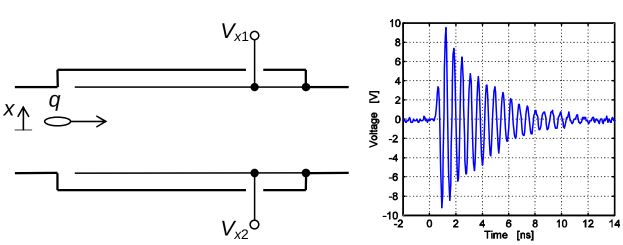

Figure 4: *Resonant stripline pickup and waveform.*

Pillbox Cavity Pickup

A cavity is a step discontinuity in the beam pipe diameter. It supports an infinite number of electro-magnetic modes. For BPMs the two lowest order modes are employed: The monopole mode TM_{010} providing a signal proportional to the bunch charge, and the dipole mode TM_{110} providing a signal proportional to the bunch charge times beam position.

An example of a high resolution single-shot cavity has beem presented in [7], and is sketched on the left side of Figure 5. It operates at 5.7 GHz, with a Q_L of 130, and provides a resolution of 25 nm at 1 nC. The beam pipe diameter is 20 mm. This example illustrates nicely that cavities can provide very high position sensitivity, while still being easy to manufacture.

Loaded Q values may range from 100 to 6'000. The mechanical and electrical center is defined accurately because of rotational symmetry. A reference pickup may be required for detection and normalization. The reentrant cavity [8] is a space saving variant.

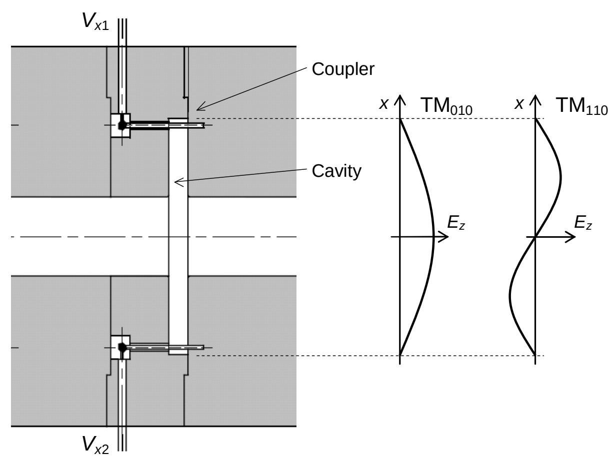

Figure 5: *Cavity pickup [7], and E_z field distributions.*

Signal Spectra of Pickup Candidates

The spectra of the three pickup types discussed are shown in Figure 6. Means to separate the difference or dipole mode signal (D) from the sum or monopole mode signal (M) depend on their spectral overlap. For striplines, only modal separation by a 180° hybrid is feasible. For the cavity, separation by frequency filtering and synchronous detection is also possible. Further, specially designed couplers may be used which inherently reject the monopole mode [9].

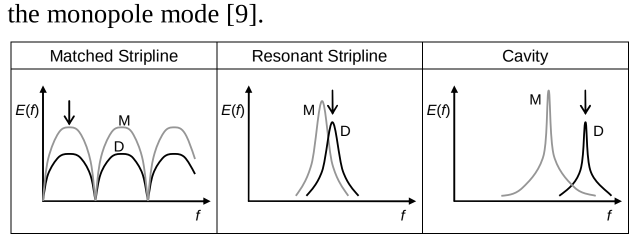

Figure 6: *Pickup signal spectra. Higher order modes of resonant stripline and cavity are not shown.*

ANALOG FRONT END ELECTRONICS

To handle the microwave signals produced by resonant pickups, analog front end electronics are required. Direct sampling of the pickup signals is not yet feasible due to dynamic range and jitter limitations of current digitizers. Analog processing schemes have been described in [10].

Log Ratio Method

A position estimate $x \sim \log(V_{x2} / V_{x1})$ can be obtained by passing the pickup signals through logarithmic amplifiers, and subtracting their outputs. However, the linearity error of practical logarithmic amplifiers of ~0.3 dB would lead to a charge dependent position error of ~150 µm.

AM/PM Method

Converting the amplitude differences of pickups signals from opposing electrodes to phase difference by a 90° hybrid and using a phase detector results in a position estimate of $x \sim \mathrm{atan}(V_{x2} / V_{x1}) - \pi/2$. The problem of this method with respect to high resolution is the phase detector: Limited sensitivity and additional nonlinearity when using a mixer, or the limited operating frequency and increased noise when using an XOR logic gate.

Wide Band Time Normalizer

This method converts the amplitude difference of impulse signals into a time difference. The requirement on the input signal of having a single zero crossing limits this method to button or matched stripline pickups. It provides, like the log ratio and the AM/PM methods, intrinsic charge normalization and is insensitive to beam phase. However, position resolution better than 5 µm and operation beyond 500 MHz have not been demonstrated yet. Estimation of resolution is complicated by the non-ideal effects of the fast comparator circuits involved. This method can be viewed as a baseband realization of the AM/PM method, thus it cannot handle ringing signals.

Δ and Σ Preprocessing and Synchronous Detection

High linearity and low noise can be obtained by first separating the difference and sum signals (Δ and Σ) using a 180° hybrid, followed by synchronous detection and digitization. The normalization $x \sim \Delta / \Sigma$ is done digitally. A fast look-up table based division algorithm may be used (Σ fluctuates only by ~15 %). The method is highly suited for cavity pickups having monopole-mode rejecting couplers, saving the 180° hybrid. For the resonant stripline, the resolution limit is given by the finite common-mode rejection of the 180° hybrid.

Instead of synchronous detection, downconversion to a low IF, with single ended or I/Q mixing, and subsequent digitization, is an alternative. The price for the resulting increase in flexibility is analog hardware, complex digital postprocessing, and latency.

Analog front ends for cavity pickups are presented in [7][8][9]. A front end for a resonant stripline is discussed below.

ELECTRONICS FOR RESONANT STRIPLINE PICKUP

An analog front end based on processing of Δ and Σ signals is presented for a 1.6 GHz resonant stripline pickup. See Figure 7 for a block diagram. The processed Δ and Σ baseband signals are subsequently digitized for postprocessing.

The main difficulty lies in the separation of the Δ and Σ signals. To achive a crosstalk of better than -40 dB, total amplitude and phase imbalances in the pickup, cables and 180° hybrid must not exceed 0.12 dB and 0.8° simultaneously. A phase error of 0.8° at 1.6 GHz corresponds to a cable length mismatch of 0.27 mm ($\varepsilon_r = 2.3$). This indicates that crosstalk in the order of -60 dB can only be obtained by applying amplitude and phase tuning.

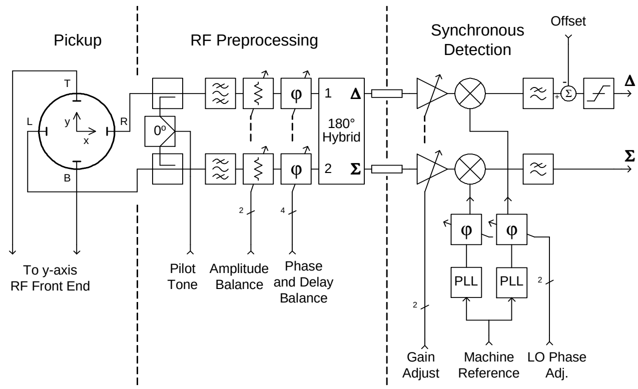

Figure 7: *Analog front end for resonant stripline [1].*

When exciting the pickup monopole mode by injecting a pilot tone from the y-axis path, electronically variable differential attenuators and phase shifters are tuned to cancel the Σ signal leaking into the Δ output of the hybrid. This procedure is repeated periodically between bunch trains. Due to the frequency difference between the monopole and dipole modes, imperfect cancelation of the Σ signal on the Δ output leads to a time-varying offset which is difficult to remove in postprocessing.

The intention of the ringing bandpass filters at the front end input is to stretch the pickup signals and flatten their peaks. This has the benefical effects of a) reducing the peak amplitude to avoid nonlinear distortions in the electronic tuning elements and mixer, b) reducing the signal envelope variation to minimize dynamic range (digitizer bits) and sampling jitter requirements, and c) creating the possibility of averaging over more samples. Stripline technology is used to obtain filters with closely matched frequency responses.

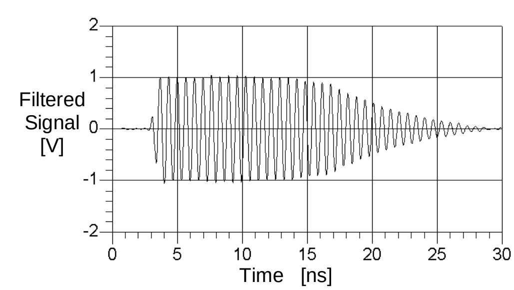

Figure 8: *Signal from resonant stripline pickup after microwave FIR ringing filter matched to the pickup Q.*

A simple form of a ringing filter is a Gaussian bandpass filter. Greater flexibility for shaping the pulse envelope is possible with microwave FIR techniques. The effect of a 21-tap microwave FIR ringing filter on the pickup waveform from Figure 4 is depicted in Figure 8. After synchronous detection, the envelope of the ringing signal is obtained.

The reference signals for synchronous detection are derived from the highly stable machine clock. Because the monopole and dipole mode signals from the resonant stripline pickup have unequal frequencies, independent LO sources and phase shifters are required.

SUMMARY

Design considerations for fast beam position monitors delivering high resolution on a bunch-by-bunch basis have been discussed. Both the resonant stripline and cavity pickups have been discussed because of their potential of providing large output signals and high sensitivity. Analog signal processing by first separating the Δ and Σ signals using a 180° hybrid, and subsequent synchronous detection was found to be advantageous with respect to linearity and noise. Analog front end electronics for a stripline pickup has been presented. Compensation of the finite crosstalk of a 180° hybrid by electronic tuning, and ringing filters for easier signal handling have been discussed.

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