BEAM POSITION MEASUREMENT WITH SUB-MICRON RESOLUTION

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Abstract

This paper gives an overview of transverse sub-micron beam position measurement systems and techniques for 3rd and 4th generation light sources and collider projects. Topics discussed include mechanical, electrical, and digital design aspects, environmental influences, machine operation and design considerations, as well as system- and beam-based measurement and calibration techniques.

INTRODUCTION

Beam position measurement (BPM) systems belong to the most vital instrumentation systems of particle accelerators. The following sections discuss selected aspects of high-resolution BPMs, with a focus on the requirements of linac-based 4^{th} generation (4G) FEL light sources in comparison to 3^{rd} generation (3G) ring accelerators. However, due to the large technological overlap between light sources and colliders, most BPM-related topics are equally relevant for both accelerator types. The scope of the discussion in the following sections is limited to RF BPMs and does not cover the large variety of alternative beam position measurement techniques like mechanical or laser wires, screens, photon detectors, residual gas, beam loss or halo detectors.

REQUIREMENTS AND APPLICATIONS

Beam Stability

The main objective of submicron resolution BPMs in 3G light sources is the measurement of the electron beam position at the photon beam line source points. Typical photon beam stability requirements for experiments at the beam line end stations translate into $\sigma/10$ position and/or $\sigma'/10$ angular stability of the electron beam at the source point. Due to a typical emittance coupling in the order of 1% or less, the vertical beam stability is usually at least an order of magnitude more critical than the horizontal one. Vertical electron beam sizes of 2-5µm in low-beta insertion devices of modern low-emittance storage rings result in position stability requirements of a few 100nm.

Electron beam movements significantly below ~100Hz may be directly visible as an undesired modulation in the time structure of the recorded experimental data of photon beam line end stations. Movements at much higher frequencies are often averaged out by the experiment and are thus perceived as an effective increase of the electron beam emittance, with an accordingly reduced effective photon beam brilliance.

The required electron beam stability in 3G light sources is usually ensured by a fast orbit feedback (FOFB) system that measures and corrects the beam positions with sufficiently fast BPM electronics and corrector (dipole) magnets. Typical FOFB systems apply corrections at a rate of several kHz, with overall feedback loop latencies in the order of some 100µs to 1ms. This allows suppression of perturbations due to e.g. mechanical magnet vibrations, power supply noise, or changing insertion device gaps. Most FOFB systems suppress perturbations up to a cut-off frequency in the order of 100-200Hz [1].

BPM requirements for 3G storage rings are primarily driven by FOFB systems, since BPM electronics noise and drift as well as movements of BPM pickup mechanics are modulated back onto the beam or even amplified by the feedback loop if they exceed its cut-off frequency. Noise and drift of the BPM system within the FOFB bandwidth of some 100Hz should therefore be lower than the desired beam stability of typically some 100nm.

In contrast to 3G ring accelerators with continuously circulating bunches and typical bunch spacings of a few ns, 4G linac-based light sources often operate in single-bunch mode, at typical bunch repetition rates of 10-100Hz. This limits the cut-off frequency of beam-based transverse feedback systems to about 1-10Hz, thus not allowing to suppress perturbations induced e.g. by girder vibrations or power supply noise in the order of some 10Hz. Consequently, such 4G accelerators must be inherently stable and need a very careful design of mechanical and electrical subsystems in order to achieve sufficient beam stability. Therefore, the BPM requirements of 4G accelerators are not primarily driven by the requirements of fast feedbacks: Their BPMs only allow to observe fast perturbations and to identify their sources, but not their active suppression.

An exception are 4G linear or re-circulating energy recovery accelerators with bunch repetition rates above ~1kHz that may operate in CW mode, or superconducting pulsed accelerators with long accelerating RF pulses like ILC or the European X-Ray FEL (E-XFEL) where trains of several 1000 bunches with 200ns bunch spacing and ~10Hz repetition rate allow the implementation of intra bunch train feedback systems [2] with sub-microsecond latency that are able to suppress perturbations from DC up to a cut-off frequency in the order of 100kHz.

4G hard X-Ray FEL accelerators typically have round beams with σ~30-40µm in the undulators, while modern 3G accelerators with usual emittance couplings of 0.1-1% have flat beams with typically 2-5µm vertical size and at least an order of magnitude larger horizontal size. Thus, the absolute transverse stability requirements of 4G accelerators in both planes are similar to the horizontal plane in 3G rings and relaxed compared to the vertical plane in 3G rings. However, future 4G SASE FELs might operate at very low emittance and bunch charge (~10pC or less) in order to lase in single-spike mode with beam sizes below 10µm in the undulators [3], thus converging towards the vertical stability requirements of 3G rings.

Beam Based Calibration and Alignment

In 3G rings, the beam position displayed by an uncalibrated BPM and the real position as defined by the magnetic centers of adjacent (well-aligned) quadrupole magnets can differ by some 100µm due to mechanical tolerances of the pickup and imperfections of the electronics. This undesired offset is usually measured by varying the beam position in each quadrupole and determining the position where a change of the quadrupole focussing strength has minimal impact on the global beam orbit. BPM resolution and drift requirements for such beam based calibration methods in 3G rings are usually in the order of 10µm or more at ~1Hz bandwidth, which is relaxed compared to the requirements imposed by FOFB systems. The main goal of beam based BPM offset calibration with subsequent adjustment of the beam orbit to the quadrupole magnet centers is the reduction of coupling and thus vertical beam size, assuming that quadrupoles and sextupoles are sufficiently well aligned relative to each other.

In contrast to 3G rings, beam based BPM calibration and magnet alignment methods in 4G linac-based FELs may impose very high requirements on BPM performance. SASE linac FELs may have undulators with overall lengths in the order of 200m that typically consist of segments of a few meters length, with a quadrupole and BPM between adjacent segments. In order to achieve reproducible lasing and photon pulse saturation within the available undulator length, the trajectory of the electron bunch should not deviate more than ~σ/10 from a tangential straight line to the usually slightly curved beam trajectory over a few nominal gain lengths (typically over ~10-20m) at any position in the undulator.

A common method to obtain the required trajectory straightness and electron-photon beam overlap is the so-called dispersion-free steering (DFS) method [4] where the quadrupole magnet centers are adjusted iteratively by mechanical movers or dipole correction coils until the trajectory becomes (nearly) independent of the beam energy for a fixed beam position and angle at the undulator entrance. This is basically equivalent to a minimization of the integrated dipole field along the trajectory, which should thus result in an optimal trajectory straightness. One advantage with respect to other methods where e.g. the trajectory variation as a function of the quadrupole magnet current is measured is the fact that DFS accounts for all undesired dipole fields. Such fields may not only result from quadrupole magnet position offsets, but also e.g. from undulator field errors, external stray fields, or the Earth's magnetic field. It should be noted that the DFS method only requires the measurement of the relative position change with energy. Initial absolute position offsets of BPMs and quadrupoles relative to the ideal beam trajectory up to several σ due to mechanical alignment errors and electronics offsets are uncritical since such offsets are measured and corrected by the DFS method. The BPM resolution required for the DFS method in order to achieve typical acceptable quadrupole magnet alignment errors of ~1µm for hard X-ray FELs [5] scales with the maximum relative energy variation that can be applied: A variation in the order of some 10% may result in BPM resolution requirements in the order of σ/30, while a accelerator that only allows a few percent variation may need ~σ/300 resolution and drift over the duration of the measurement. However, depending on the way the measurement is performed and the accelerator is operated, this resolution and drift may not necessarily be required for single bunches but may be obtained by averaging over several bunches or measurement iterations.

ACCELERATOR DESIGN AND OPERATION ASPECTS

The design of an accelerator facility and the way it is operated have a large impact on the BPM requirements for a given accelerator performance goal. The following sections discuss some related design and operation considerations.

Bunch Shape

While the longitudinal and transverse charge distribution of a single electron bunch in a 3G light source is usually quasi-Gaussian due to synchrotron radiation damping, 4G accelerators may have very complex non-Gaussian asymmetric distributions in all 3 dimensions caused mainly by longitudinal bunch compression schemes in combination with nonlinearities of the accelerating RF fields.

In 4G SASE FELs, such charge distributions may entail that the part of the bunch with sufficient charge density for lasing has a transverse offset in the order of the bunch size relative to the center of charge that is measured by RF BPMs [6]. While this is irrelevant for beam-based magnet alignment techniques like e.g. the DFS method, it may cause problems for RF BPM based beam position feedbacks meant to correct the beam trajectory e.g. in the undulators: The BPMs may display a perfectly straight trajectory, while the part of the bunch with enough charge density for lasing performs large betatron oscillations around the desired straight trajectory so that the spatial overlap with its generated photon field is not sufficient for stable SASE operation. In order to avoid this, 4G accelerator facilities usually employ higher-harmonic RF systems that linearize the accelerating RF fields, leading to charge distributions with a sufficiently small offset of the lasing part of the bunch relative to the center of charge.

Magnet Lattice and BPM Pickup Locations

Many transverse feedback systems in 3G and 4G light sources and colliders use the singular value decomposition (SVD) method, where the changes of the corrector magnet kicks ΔK_j that are required to achieve a desired change of the beam positions ΔB_i are calculated using pseudo-inversion of the beam response matrix $M_{ij} = \Delta B_i / \Delta K_j$ that can be obtained either by measurement or by a theoretical optics model. M can be written as product

$M = U\Sigma V^T$, where U and V are orthonormal square matrices, and Σ is a diagonal matrix with only non-negative elements $\Sigma_{ii}=\lambda_i$, the so-called singular values of M that are usually sorted in descending order. The pseudo-inverse of M is $M^+=V\Sigma^+U^T$, with $\Sigma^+_{ii}=1/\lambda_i$ for $\lambda_i \neq 0$ and $\Sigma^+_{ii}= 0$ otherwise. The quotient $C=\max(\lambda_i)/\min(\lambda_i)$, $\lambda_i \neq 0$ is called conditioning number. The positions of BPMs and magnets in an accelerator as well as the beam optics should be designed in a way that minimizes C, since a large value of C means that at least one orbit perturbation pattern (represented by the i^{th} row vector of U^T that belongs to the smallest λ_i) requires a C-times larger RMS change of the corrector magnet kicks than another pattern (represented by the row vector that belongs to the largest λ_i) in order to obtain a certain RMS orbit change. Since (uncorrelated) BPM electronics noise contributes equally to all measured BPM patterns while real orbit perturbations are usually dominated by patterns belonging to large λ_i, a fast trajectory feedback in a accelerator with e.g. C=100 may cause ~10x larger noise-induced perturbations than in a accelerator with C=10.

Many accelerators with large C values therefore set small λ_i to 0 (singular value cut-off). This reduces the BPM-noise induced orbit perturbations, but also causes the feedback not to correct certain orbit perturbation patterns, so that the beam positions are usually not corrected exactly to the desired values. Alternatively, all λ_i below a certain limit (but still above the noise level) can simply be set to larger values before performing the pseudo-inversion. Then the respective perturbations are still corrected, but with a smaller feedback loop gain than other perturbations, thus reducing the amount of BPM noise being modulated onto the beam by the feedback [7].

In addition to a small conditioning number C, 3G and 4G accelerators should be designed with large beta functions at the locations of BPMs (preferably without increasing C), especially in case of BPMs adjacent to insertion devices that are used by orbit feedbacks, since the contribution of BPM electronics noise and drift to the photon beam movement for given optical functions at the photon beam source point scales with $1/\mathrm{sqrt}(\beta_{BPM})$.

Bunch Charge Stability

Differences between measured and real beam position due to electronics nonlinearities usually depend on the (average) beam current or bunch charge as well as on the temporal charge variation of subsequent bunches in linear and circular accelerators (for a constant average current). While this bunch charge dependence can be reduced by suitable electronics design and calibration techniques, it may still be large enough to have an undesired impact on beam stability. In 3G ring accelerators, this can be avoided by keeping the beam current at a nearly constant level by sufficiently frequent injections ("top-up injection") [8], and by using a "filling pattern feedback" [9] that not just keeps the overall beam current but also the relative charge distribution among the different RF buckets constant. Such feedbacks not only relax the BPM electronics requirements with respect to linearity and bunch charge dependence for a given beam stability goal, but they also improve the medium- and long-term photon beam stability drastically by keeping the thermal load on the beam pipe and photon beam line optics components nearly constant.

Environmental Aspects and Non-RF BPMs

Variations of the environmental temperature cause mechanical drift of BPM pickups as well as drift of BPM electronics components, e.g. gain and offset drift of amplifiers, attenuators, mixers or ADCs. The resulting temperature-dependent beam position offset due to mechanical pickup drift can be measured on-line with suitable sensors and added to the measured beam position. Temperature-induced drift of the beam position caused by BPM electronics components can be reduced by suitable design techniques. However, it may still be desirable or necessary to control and stabilize the air temperature and air flow speed in the area of BPM pickups and electronics in order to improve the beam stability. Additionally, non-RF BPMs like photon BPMs can be used to improve the photon beam stability in 3G and 4G light sources, e.g. by correcting the reference orbit of an RF BPM based FOFB in a way that keeps the photon beam positions constant [10]. Thus, any bunch charge and temperature drift effects of RF BPM electronics within the correction bandwidth of the photon BPM feedback become irrelevant for the photon beam stability.

BPM PICKUPS AND ELECTRONICS

Table 1 contains a qualitative overview of the properties of some RF BPM pickup types with respect to performance requirements, design effort, and costs. The table is based on a somewhat subjective selection and evaluation of existing pickups. A "+" (or "++") symbol indicates that it is usually less (or much less) challenging to meet a requirement or to keep the design effort or costs low, while a "-" (or "- - ") symbol denotes that it is more (or much more) challenging to reach the respective goal.

Table1: Qualitative Properties of Various BPM Pickups

	Button	Matched Stripline	Resonant Stripline, Normal Coupling	Single Cavity Normal Coupling	Two Cavities, Hybrid Coupling	
Signal/Noise	–	– / +	+	+	+	
Monopole Mode Suppression	–	–	–	– / +	+	Performance
Single-Bunch Resolution (@ Low Charge)	–	– / +	+	+	++	
Electronics Drift	– / +	– / +	– / +	– / +	+	
Weight 10mm Pipe	+ +	+	+	+	+	
Weight 40mm Pipe	+ +	– / +	– / +	– / +	– / +	
Design Effort	+ +	– / +	– / +	– / +	–	Budget
Fabrication Costs	+ +	– / +	– / +	– / +	– / +	
Tuning Effort	+ +	+ +	– / +	+	+	

Button Pickups

Most 3G storage rings use button pickups, since they are inexpensive, have minimal impact on the beam, and a broadband spectrum that allows to use commercial types for different accelerator RF frequencies. Since submicron resolution is usually only required within the FOFB bandwidth below 1kHz where the overall integrated beam charge for 3G accelerators during user operation is usually >100µC, the signal-to-noise ratio is uncritical, and a resolution of some 100nm can be reached with moderate electronics design effort. This is different in 4G linac-based FELs, especially for single-bunch operation with 10-1000pC bunch charge at 10-100Hz rep rate, where the single-shot position resolution of button BPM systems is usually ranging from a few microns to tens or even hundreds of microns depending on bunch charge and pickup geometry.

Striplines

Matched or resonant stripline pickups are typically used for beam transport lines where single bunches have to be measured with higher precision than achievable with button pickups. The signal level and spectrum of stripline pickups enable higher signal-to-noise ratio, especially in case of resonant striplines The output signal of matched striplines consists of two pulses with opposite polarity, where the pulse spacing is twice the flight time along the four pickup strips. Resonant striplines are basically four $\lambda/4$ resonators with 90° rotation symmetry parallel to the beam. Their output signal is an exponentially decaying sine at the fundamental mode frequency (determined by the strip length) plus harmonics at odd integer multiples of that frequency. Since the four strips are individual resonators with mutual coupling, the pickup actually has four fundamental modes: A monopole mode proportional to the bunch charge, two dipole modes proportional to the product of bunch charge and horizontal or vertical position, and a quadrupole mode. The natural frequency separation between these modes is typically a few percent, although monopole and dipole mode frequencies can be matched by using non-uniform strip widths that increase towards the open end of the strip [11].

Monopole and dipole mode signals of resonant stripline and single-cell cavity BPMs (see below) can be separated using an external hybrid followed by bandpass filters. Resolution and drift are typically limited by the imperfect suppression of the monopole mode in the dipole channel of the electronics.

Cavities

While the performance of button and stripline BPMs is usually sufficient for beam transport lines, most 4G FEL undulators are equipped with cavity BPM pickups that allow to reach sub-micron resolution even at low charges. The simplest cavity BPM pickup consists of a single cylindrical cavity with four 90° rotation symmetric electrodes that couple directly to the resonator. The beam position is obtained by dividing the amplitude of the TM_{11} (“dipole”) mode that is proportional to the product of bunch position and bunch charge through the TM_{01} (“monopole”) mode amplitude that is only proportional to the bunch charge. A comparatively large spectral mode separation of typically some 10% allows easier monopole mode suppression in the electronics via band-pass filters as compared to stripline pickups. However, the different frequencies of dipole and monopole mode may cause significant temperature-induced position drift due to frequency-dependent properties of electronics components in monopole and dipole signal channel.

In order to overcome these drawbacks, several 4G linac FELs use cavity BPMs consisting of two adjacent, usually cylindrical cavities, one for the dipole and one for the monopole mode signal, with the same frequency of typically 3-12GHz for both signals. The dipole cavity often uses a mode-selective (“hybrid”) coupling scheme [12] where more or less short waveguides couple only to the desired dipole mode while suppressing other modes, thus enabling a much lower drift- and resolution-limiting monopole mode leakage into the dipole signal channel.

Cost and Performance Aspects

Recent progress in the design of cost-optimized dual-cavity pickups with mode-selective couplers [13] allows their production at costs comparable to stripline pickups. Therefore 4G accelerators like the European XFEL plan to use dual-cavity pickups where high resolution is needed, and inexpensive button pickups elsewhere in the beam transport lines, without a third “medium-resolution” pickup type like matched or resonant striplines. However, striplines are still an attractive option for accelerators operating at very low bunch charge, e.g. for locations in the accelerator where the beam pipe diameter is too large for cavity BPMs (that tend to become large, heavy and expensive for large pipe diameters) and where the resolution of button pickups is not sufficient.

Electronics

Figure 1 shows simplified sketches of typical architectures of 3G ring button BPM (top) and 4G linac cavity BPM electronics (bottom). Modern 16-bit ADCs with 100-200MSamples/s and a bandwidth well above 500MHz allow direct sampling of button pickup signals at the main RF frequency of 3G ring accelerators, with a comparatively small analog input stage consisting mainly of bandpass and amplifier/attenuator stages.

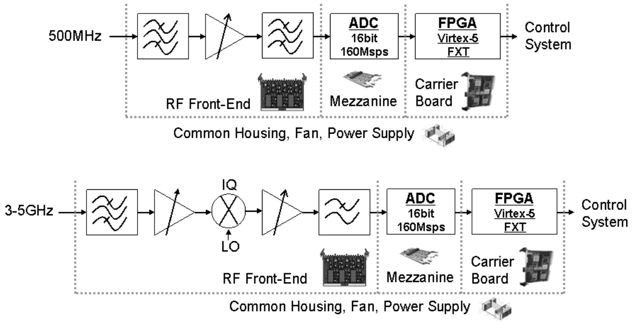

Figure1: BPM electronics for 3G and 4G light sources.

The main challenge is often not the required resolution of typically some 100nm at ~1kHz bandwidth but a low temperature drift and beam charge dependence in the same order as the resolution. Common electronics design techniques to reduce drift and charge dependence include single- or multi-channel multiplexing schemes, real-time normalization on pilot signal tones, active temperature stabilization, or the compensation of nonlinearity and drift using lookup tables obtained by a lab calibration setup.

Since matched or resonant stripline pickup signals usually have a significant amount of their spectral energy within the bandwidth range of fast high-resolution ADCs, their signals can be sampled directly using similar electronics than storage ring button BPMs, typically with higher input stage gain, and resolutions down to a few microns for higher bunch charges. An alternative direct sampling approach for single-bunch linacs is the use of single-shot waveform digitizer chips that allow extremely cost-efficient recording of raw or bandpass-filtered BPM pickup signals at several GSamples/s [14].

Dual-cavity BPMs generate decaying sine signals with a typical frequency of 3-12GHz and loaded Q values in the order of 100 to several 1000. While higher frequencies theoretically enable higher resolution, lower frequencies allow larger pipe diameters, more flexibility and larger tolerances with respect to electronics components, as well as the use of several meters of cable from pickup to electronics instead of rigid waveguides that are used e.g. for X-band cavity BPMs in order to limit the signal attenuation to reasonably small values. Cavity BPM electronics usually employ IQ mixing to an IF in the order of 100MHz or to baseband before sampling the signals with high-resolution ADCs. An overview of existing high-resolution cavity BPM pickup and electronics designs can be found in Ref. [15].

Since ADC and digital signal processing electronics for 3G ring and 4G linac BPM electronics have very similar requirements, accelerator labs with both accelerators types may design generic BPM electronics consisting of pickup-specific RF front-ends and a common digital back-end and ADC type. In addition to FPGA- or ASIC-based digital IQ downconverters for direct sampling or IF-based BPM systems, digital back-ends [16,17] of modern BPM systems usually have serial multi-gigabit fiber optic or copper cable links that allows their integration into 3G ring FOFBs or 4G linac intra-bunchtrain feedback systems, with the possibility to use the same communication protocols, timing and control system interfaces for both accelerator types.

SUMMARY

Beam position measurement with sub-micron resolution and drift does not only involve BPM pickup and electronics technology, but should be based on an overall concept regarding the design and operation of an accelerator and its subsystems. The BPM system requirements for fast transverse feedbacks or beam based alignment in 3G and 4G light sources and colliders can be significantly relaxed by suitable accelerator design, alignment and operation techniques. BPM system architectures with accelerator-specific pickups and RF front-end electronics combined with generic digital-backend and ADC solutions enable large synergies between different accelerator types.

REFERENCES

[1] N. Hubert et al., *"Global Fast Orbit Feedback System Down to DC using Fast and Slow Correctors"*, these proceedings.

[2] B. Keil et al., *"Design of an Intra-Bunch-Train Feedback System for the European X-Ray FEL"*, Proc. DIPAC'07, Venice, Italy, 2007.

[3] Y. Kim et al., *"Beam Diagnostics and RF System Requirements for the SwissFEL Facility"*, these proceedings.

[4] T. Raubenheimer et al., *"A Dispersion Free Trajectory Technique for Linear Colliders"*, NIM A302:191-208, 1991.

[5] Y. Li et al., *"Impact of Quadrupole Offset and Undulator End-Kicks on the European-XFEL Facility Performance"*, DESY TESLA-FEL Report 2009-4, May 2009.

[6] B. Faatz et al., *"Status of FLASH and the European XFEL"*, SINAP'08, Shanghai, China, 2008.

[7] M. T. Heron et al, *"Performance and Future Developments of the Diamond Fast Orbit Feedback System"*, Proc. EPAC'08, Genoa, Italy, 2008.

[8] T. S. Ueng et al, *"Topping Up Experiments at SRRC"*, Proc. EPAC'96, Sitges, Barcelona, Spain, 1996.

[9] B. Kalantari et al., *"Bunch Pattern Control in Top-Up Mode at the Swiss Light Source"*, Proc. EPAC'04, Lucerne, Switzerland, 2004.

[10] T. Schilcher et al., "*Commissioning and Operation of the SLS Fast Orbit Feedback*", Proc. EPAC'04, Lucerne, Switzerland, 2004.

[11] A. Citterio et al., *"Design of a Resonant Stripline Beam Position Pickup for the 250 MeV PSI XFEL Test Injector"*, these proceedings.

[12] Z. Li et al., *"Cavity BPM With Dipole-Mode Selective Coupler"*, Proc. PAC'03, Portland, Oregon, USA, 2003.

[13] H. Maesaka et al., *"Beam Position Monitor at the SCSS Prototype Accelerator"*, Proc. APAC'07, Indore, India, 2007.

[14] B. Keil et al., *"Application of a 5 GSPS Analogue Ring Sampling Chip for Low-cost Single-shot BPM Systems"*, Proc. EPAC'08, Genoa, Italy, 2008.

[15] D. Lipka, *"Cavity BPM Design, Related Electronics and Measured Performances"*, these proceedings.

[16] A. Kosicek, *"Libera Electron Beam Position Processor"*, Proc. PAC'05, Knoxville, Tennessee, USA, 2005.

[17] B. Keil et al., *"The PSI VPC Board - First Applications of a Common Digital Back-End for Electron and Proton Beam Instrumentation at PSI"*, Proc. DIPAC'05, Lyon, France, 2005.