OVERVIEW OF FAST BEAM POSITION FEEDBACK SYSTEMS

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Abstract

Modern circular and linear accelerators often rely on fast beam position feedbacks for the achievement of their design parameters. Such systems have gone through a significant evolution, which has taken advantage of recent progress of the associated equipment, like beam position monitors, as well as of the hardware and software processing technologies. A review of the latest developments and foreseen designs at different accelerators is given.

INTRODUCTION

Precise control and stability of the beam trajectory are essential to the successful operation of different types of particle accelerators. In addition to a careful accelerator design and a continuous identification and minimization of the noise sources, feedback systems have become crucial for the attainment of the trajectory stability goals. Fast beam position feedbacks, in particular, are fundamental in those cases where requirements for short (ms-s) and medium (minutes-days) term stability are strictest. With this respect, fast beam position feedback developments are herewith organized in the following major areas.

With the objective of delivering higher brightness photon beams to the beam line users, emittance values of storage ring based synchrotron radiation sources have been reduced down to the level of a few nm·mrad. Given the optimized optical functions and the ability to control and minimize coupling to some tenths of percent, vertical beam size and divergence at the Insertion Device (ID) source points can be well below 10um and 10urad respectively. Despite the fact that different kinds of user experiments may have specific requirements [1], the typical stability goal is to keep the electron beam position and angle at the source point within a few percent (at least <10%) of the respective size and divergence over time periods ranging from ms to days, which leads to sub-micron level stability on such a time span [2].

Given the huge beam stored energy to be handled in a mostly superconducting environment, the LHC is the first hadron collider that requires continuous orbit control for safe and reliable machine operation. The tightest constraints are set by the Cleaning System collimators, which prevent magnet quenches due to regular beam diffusion and whose efficiency critically depends on the beam orbit. The requested stability is 1/6 of the rms beam size, which corresponds to about 25um at the collimator jaws. The global orbit should also be controlled within 0.5mm rms throughout all the different machine operational phases.

Electron/positron linear accelerators are adopted to drive the next generation of colliders and synchrotron radiation sources based on single-pass Free Electron Lasers (FEL). In order to reach the foreseen luminosity in linear colliders, high intensity beam pulses, each made of multiple bunches, are accelerated keeping the small emittance provided by preceding damping rings. Emittance preservation requires precise control of the beam trajectory based on data from high resolution single-pass Beam Position Monitors (BPM). In particular a ‘golden’ path, which reduces or compensates for the effect of wake fields excited by the high current bunches in the accelerating structures and minimizes quadrupole induced dispersion, must be carefully maintained.

Similarly, in a single-pass FEL the linac accelerates single or multi-bunch beam pulses emitted by an electron gun avoiding dilution of the original low emittance (typical normalized emittance is 1-2mm·mrad). Magnetic chicanes are inserted to compress the bunch length and achieve the requested high peak current (few kA). Once in the undulator part, the overlap between the electron beam and the emitted radiation must be tightly kept along distances up to some hundreds meters. Given the emittance values above and by assuming final beam energies in the range of some GeV, the beam diameter at the location of the undulators is typically of a few tens of um. By taking a stability goal of less than 10% of the beam size, the single-pass beam trajectory in the undulators has to be stabilized within a few um.

To maintain the foreseen luminosity in colliders, beam trajectories at the Interaction Point (IP) must be stabilized to a fraction of the design beam spot size.

SOURCES OF INSTABILITY

Typical short and medium term instabilities affecting the particle trajectory in accelerators are induced by mechanical displacement of the magnets and, in particular, of quadrupoles. These, in turn, are driven by natural and cultural ground motion, thermally induced effects, cooling liquid flow, etc. Other sources of instability are current power supplies noise that contains harmonics of the mains frequency, external stray electrical and magnetic fields.

In a storage ring synchrotron light source [1], gap and phase changes of the IDs, including fast polarization switching devices, can induce significant distortions to the orbit.

Specific sources of orbit distortion at the LHC [3] are dynamic effects of superconducting magnets, like snapback and decay or ramp-induced effects, and beta squeeze of the final focus optics in the experimental insertions.

Compared with circular accelerators, the electrons trajectory in a linac is open and does not take advantage of any physical effect that damps transverse oscillations [4]. Higher frequency noise components result in pulse to pulse beam deviations, often called jitter. Variations of the injected beam, dynamic displacement of the quadrupoles and of the accelerating structures are among the main noise sources. Moreover, there are many mechanisms where jitters can be transformed from one type to another, which make it difficult to identify the primary noise source.

Particular sources of instability in the IP region are the vibrations of the final focusing magnets induced by ground motion and mechanical disturbances.

FEEDBACK & FEED FORWARD DESIGN

Feedback or closed-loop control of an output variable of a physical dynamic process is quite a common concept [5]. It consists of measuring the controlled variable through a sensor, comparing its value to a desired reference and using that information inside the controller to influence the value of the controlled variable itself.

If the dynamic behaviour of each system component is mathematically modelled by the familiar notion of transfer function, it can be seen that in the closed-loop configuration the controller changes the overall system transfer function and therefore its dynamics. This is the basic feature of the feedback scheme. Feedback controllers are eventually designed by manipulating the locations of the poles of the closed-loop transfer function to meet some performance specifications, like reducing the effects of external disturbances or noise on the output, improving the transient response by increasing the system bandwidth and the speed of response, reducing the sensitivity to variations in system parameters. Transform techniques usually lead to the design of quite robust closed-loop systems, which tend to be insensitive to small inaccuracies in the adopted model, and are well suited for Single-Input Single-Output (SISO) systems. In the case of a Multi-Input Multi-Output (MIMO) system, different strategies are adopted to transform it into multiple non-interacting SISO feedback loops.

In a typical beam trajectory feedback, BPMs are used as sensors, corrector dipole magnets or electromagnetic kickers fed by appropriate power supplies as actuators. The particle beam is the process to control. Different kinds of programmable digital processors are mostly adopted as controller.

A different and comprehensive method of designing feedback control systems is the state-space method. It consists of a sequence of well defined independent steps, structured in a powerful mathematical framework. State-space methods allow all poles of the closed-loop system to be placed in desirable locations. The price to pay for such a general approach is the need for an accurate system model, which necessitates the measurement of many system internal variables. As this is not feasible in most of the cases, an estimator (or observer) is introduced to reconstruct the values of the internal variables from the ones that can be measured. In addition to intrinsically allowing for the design of controllers for Multi-Input Multi-Output (MIMO) systems, state-space design methods give access to the most advanced methodological developments in the field of feedback systems science. Using concepts of optimal control, like the Linear Quadratic Gaussian (LQG) method, poles can be specifically located to achieve the desired trade off between dynamic system output response (e.g. rms of the measured beam positions) and control effort (e.g. rms of the corrector power supplies output currents), taking into account the relative weight of process and sensor noise.

Systematic and reproducible perturbations of the beam trajectory can be measured and successively compensated by table-driven feed forward systems.

STORAGE RING BASED SYNCHROTRON RADIATION SOURCES

In the last twenty-five years, fast beam position feedbacks have evolved from local to global systems and have developed from analog to digital electronics, driven by the technological advancement in the fields of telecommunications and digital signal processing. In a local scheme, three (or four) corrector magnets are used to create a local bump, which stabilizes the electron beam position (and angle) at the source point without affecting the rest of the orbit. In addition to minimizing the rms of the difference with respect to a ‘golden orbit’, a global feedback can support and integrate different correction strategies.

The original local feedback systems at SSRL [6] were implemented by linear analog circuits. A first global orbit feedback system was installed on the VUV ring of the NSLS [7] and was still based on analog electronics. Given the limited number of BPM input and corrector magnet output channels that could be effectively managed, the harmonic global orbit correction algorithm was used, which fully exploits the fact that the orbit distortion is dominated by its harmonic components nearest to the tune. Starting from the system at the APS [8], digital global orbit feedbacks are being developed that include a large number or all of the available BPMs and corrector magnets.

The correction algorithm is typically based on the inversion of the response matrix, which relates the beam position at the location of the BPMs with the corrector magnets kicks, using the technique of Singular Value Decomposition (SVD). In addition to being a powerful mathematical method for matrix inversion in the case of an arbitrary number of BPMs and correctors, SVD remaps the original system in a transformed space where each transformed BPM is coupled to at most one transformed corrector through a single coefficient that is proportional to the correction strength of the considered correction channel. Such coefficients correspond to the singular values of the diagonal response matrix in the transformed space. In order to limit the current needed by the correctors, channels with the lower singular values can be neglected at the expense of a minor reduction of the overall correction efficiency.

The remapping effect of SVD on the original MIMO system results in the possibility of implementing a SISO feedback loop on each transformed correction channel. The dynamics of each channel is dominated by the low-pass behaviour of the actuator, mainly due to eddy currents in the magnet core laminations and in the vacuum chamber wall. The other important parameter is the total latency caused by data acquisition, transmission and processing, which is in the order of some hundreds us. A correction channel can therefore be quite well approximated by a first order low-pass filter plus a delay [9]. The usual control algorithm is the Proportional Integral Derivative (PID) regulator. With feedback repetition rates up to 10kHz and an appropriate choice of the regulator coefficients, orbit noise can be effectively attenuated up to frequencies in the 100-150Hz range, which impacts most of the users' experiments. In order to overcome bandwidth limitations, a reduced number of air-core correctors can be dedicated to the fast orbit feedback, while a slow feedback using all of the available standard type correctors runs at the same time [10, 11]. Concurrent operation of slow and fast orbit feedbacks is implemented also at the APS and ALS [12, 13]. At PETRAIII, turn-by-turn beam position data are directly acquired from the BPM electronics to minimize latency.

Persistent periodic components of the noise spectrum, like those at the frequency of the mains and its harmonics, can be suppressed by specific feedback loops [14, 15]. Each loop consists of a selective digital filter with gain regulation centred at the frequency to damp plus a programmable delay, whose value is calculated in order to achieve an overall system open-loop rotation of 360° at the chosen frequency. The closed-loop system behaves as a notch filter whose depth is regulated by the programmable gain. As long as the notches are completely separated from each other, multiple loops centred at different frequencies can be implemented and run in parallel with the PID. Moreover, as the beam noise components associated with the mains are periodic and stable, their reduction is possible even if the frequency is higher than the open-loop cut-off frequency, where the phase rotation is large.

The analysis, developed at SPEAR3 [16], of the orbit error spectrum in the transformed space illustrates that 'legitimate' perturbations are associated more with the correction channels with large singular values, whereas random system noise shows up uniformly. By differently adjusting the regulator coefficients, channels with small associated singular values are assigned a reduced bandwidth to limit the effect of random noise into the loop. A similar approach is being implemented at Diamond, where the singular values are scaled using the Tikhonov regularization method [17].

Many modern global orbit feedbacks [11, 12, 13, 17, 18 and 19] are distributed computing systems, typically composed of a number of local stations, each connected to a subset of BPM detectors and corrector power supplies. Local stations are linked in a ring topology on a dedicated network that allows for sharing all of the acquired BPM data. Each local station calculates the settings needed by the associated subset of corrector power supplies using all of the BPM data and a block of the transformed inverse response matrix. Optionally, an additional station is included to perform global supervision tasks, like correcting orbit distortion due to dispersion by acting on the RF master oscillator, or performing data acquisition and processing at the full feedback rate. Clock signals with embedded event and timestamp information are distributed to all system components to synchronize BPM data acquisition, feedback algorithm calculation and actuator setting.

Different computing platforms are adopted by the various laboratories for the processing of the feedback data, including Field Programmable Gate Arrays (FPGAs), Digital Signal Processors (DSPs) and general purpose computers running real-time operating systems that are already provided by the underlying control system infrastructure. The fast and deterministic data network is based on custom designs as well as on different implementations of Ethernet, whose low-level software driver is opportunely modified. Redundant data paths are also installed to improve availability.

Feed forward systems acting on dedicated correction coils are generally implemented to compensate for the residual orbit distortion associated with the operation of the IDs and can provide good performance for slowly varying gap/phase. In the case of devices with a relatively fast switching rate (up to some tens of Hz) of the radiation polarization, specific strategies are needed for the evaluation of the feed forward look-up tables to take into account dynamic effects that arise during operation. In particular, the orbit distortion due to the ID must be clearly measured and disentangled from the background noise present in the beam. Examples are given in [14, 20].

LARGE HADRON COLLIDER

Due to the different and spatially distributed requirements, a global orbit feedback system is implemented. It consists of more than 1056 BPMs, a centralized feedback controller and 1060 superconducting correction dipole magnets. The individual systems that are distributed over the 27km ring circumference are connected through the redundant LHC technical network featuring Gbit-Ethernet and hardware based Quality of Service. The SVD correction algorithm is adopted. A PID regulator with Smith-Predictor extension is used to improve the feedback response and to compensate for constant transmission delays. The foreseen feedback rate is 25-50Hz. With the large number of BPMs and correctors involved, the development of on-line countermeasures to component failures is an essential part of the overall system design.

ELECTRON LINEAR ACCELERATORS

Two feedback types are implemented on linear accelerators. Given the typical beam pulse repetition rates between a few to about one hundred Hz, pulse to pulse feedbacks can successfully counteract the effect of drifts and noise up to a few Hz. Where relatively long trains of bunches per pulse are used, feedbacks acting on each individual bunch are being developed to cure higher frequency noise.

A significant experience with the operation of trajectory feedback systems for linear accelerators was gained with the SLC [21]. A sequence of localized orbit feedback systems was used along the three-kilometre linac. The feedback loops were designed using the state-space formalism. The LQG method was adopted to generate optimum filters that minimize the rms disturbance seen in the beam for a given noise spectrum. To avoid overcorrection by having multiple loops respond to an incoming disturbance, each system was designed to communicate information to its downstream neighbour in a ‘cascade’ scheme [22]. Each loop could be distributed across several of the standard microprocessors that controlled the SLC equipment. Due to bandwidth limitations, the loops operated at a subset of the 120Hz beam rate. The operation of the system showed that, in the presence of strong wake fields, the beam transport is different depending on the origin of the perturbation. A more complete interconnection was therefore required where each feedback got information from all upstream loops.

A fast data acquisition system (DAQ) is implemented to support pulse to pulse feedbacks up to the maximum 10Hz rate of FLASH [23]. The DAQ provides at the same time synchronized data recording of the parameters of the individual 800 1us-spaced bunches per pulse and on-line measurements for both accelerator operation and user experiments. The whole system is integrated in the DOOCS control system of FLASH and represents a combination of an accelerator control and a high performance data acquisition system proper of high energy physics experiments. About 2Gsamples data per second are collected in the shared memory of a central multiprocessor computer. Here they become available to different feedback and monitoring processes before being archived in a large storage repository.

A control system fully integrated approach is being pursued also for the implementation of the pulse to pulse beam based feedback systems of the LCLS, SCSS, ILC [24] and FERMI@Elettra.

An intra-bunch train feedback (IBFB) system is under development for the European X-FEL and will be installed behind the main linac of the facility [25]. It individually acts on the 3250 200ns-spaced bunches that constitute each 10Hz electron pulse. The proposed IBFB topology consists of two upstream BPMs followed by two kicker magnets for each transverse plane. In order to reach the overall target latency of less than 200ns, FPGAs are adopted as processing elements. They execute an FIR-based algorithm that predicts the kick necessary to correct the position of the current bunch from the measured positions of the previous ones. In parallel to the feedback, DSPs perform a slower adaptive feed forward algorithm by identifying and correcting repetitive beam perturbations that are the same from bunch train to bunch train. Two downstream BPMs are used to check and adaptively optimize the model used for the calculation of the kicks. The IBFB damps perturbations in the frequency range from a few Hz to several hundreds kHz.

INTERACTION POINTS IN COLLIDERS

In circular colliders, trajectory feedbacks implement closed local bumps to adjust the beam position and/or angle at the IP. Such systems have been recently installed at RHIC [26] and HERA-E [27]. The beam-beam deflection mechanism can be successfully exploited to determine IP beam offsets in feedback systems at electron positron colliders [28, 29]. Direct measurement of the luminosity can also be used to maintain the optimum collision conditions. As no information on the beam orbit is available, however, a direct trajectory loop cannot be implemented. Dithering techniques [30] are adopted in this case, which consist of operating sub-tolerance variations of the beam position or angle around a given value to allow measurements of the luminosity slope and subsequently changing the trajectory settings. The fast luminosity dither system for PEP-II is described in [31].

In order to compensate for the jitter induced by even extremely small (down to tens of nm) vibrations of the final focusing magnets, intra-bunch train feedbacks are foreseen to respectively correct the vertical position and angle of individual bunches at the IP of the ILC [32]. Each system uses a BPM to measure the position of early bunches in the outgoing beam and a kicker to act on the subsequent bunches of the incoming other beam. The beam-beam interaction is so strong that nm-level offsets at the IP can be inferred by measuring the downstream beam deflection with micron-level resolution. A feedback system prototype based on FPGA as processing element has been developed by the FONT (Feedback On Nano-second Timescales) project and tested at the KEK-ATF extraction beam line. The achieved total system latency is about 140ns, which is less than the minimum envisaged bunch spacing of the ILC.

CONCLUSIONS

Fast beam position feedback systems have gone through a considerable evolution, driven by the increasing requirements of accelerator applications and enabled by the progress in digital processing, telecommunication and networking technologies. Nowadays, they are well established systems and have become key components to achieve and maintain the target beam trajectory stability. While the necessary raw processing resources seem or are likely to be adequate, the increased strategic role is prompting the need and the trend towards higher levels of reliability, availability and integration. The latter, in particular, leads to the inclusion of modelling and flexible automation tools, system level and beam diagnostics. In order to minimize the impact of the resulting effort, the following approaches can be envisaged. Given the number of similarities, there is space for improving the collaboration in the development of fast beam position feedback systems among the different accelerator areas.

Intra-bunch train feedbacks, for example, have many analogies with multi-bunch feedbacks used in storage ring synchrotron radiation sources and particle factories; beam trajectory stability specifications in damping rings are very close to those in storage ring synchrotron radiation sources. Secondly, commercial-off-the-shelf components and subsystems exist and can help.

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REFERENCES

[1] R.O. Hettel, "Beam Stability Issues at Light Sources", 25th ICFA Advanced Beam Dynamics Workshop, Shanghai, China, September 2001.
[2] Proc. Third Int. Workshop on Beam Orbit Stabilization (IWBS), December 2004, Grindelwald, Switzerland, http://iwbs2004.web.psi.ch.
[3] R. J. Steinhagen, "LHC BEAM Stability and Feedback Control – Orbit & Energy", CERN-AB-2007-049 BI.
[4] T. Shintake, "Overview of Single Pass FEL Designs Technical Suggestions for Stability Improvement", FEL'04, Trieste, September 2004, MOBIS01, p. 90.
[5] G. F. Franklin, J. D. Powell and A. Emami-Naeini, Feedback Control of Dynamic Systems, Addison-Wesley Publishing Company, 1994.
[6] R. Hettel, Nucl. Inst. Meth. 155, A266 (1988).
[7] L. H.Yu et al., "Real Time Closed Orbit Correction System", PAC'89, Chicago, March 1989, p. 1792.
[8] J. A. Carwardine and F. R. Lenkszus, "Real-Time Orbit Feedback at the APS", BIW'98, AIP Conf. Proc. 451, p. 125-144.
[9] D. Beltran and M. Munoz, "Initial Design of a Global Fast Orbit Feedback System for the ALBA Synchrotron", ICALEPCS'07, Knoxville, October 2007, RPPA23, p. 561.
[10] E. Plouviez et al., "Upgrade of the Global Feedback of the ESRF Storage Ring", DIPAC'05, Lyon, June 2005, POM022, p.84.
[11] N. Hubert et al., "Design of a Fast Orbit Feedback for SOLEIL", DIPAC'05, Lyon, June 2005, POT019, p. 187.
[12] C. Schwarz, L. Emery, "Compensating the Frequency Deadband of the APS Real-time and DC Transverse Orbit Correction Systems", PAC'01, Chicago, June 2001, TPAH001, p. 1234.
[13] C. Steier et al., "Operational Experience Integrating Slow and Fast Orbit Feedbacks at the ALS", EPAC'04, Lucerne, July 2004, THPLT141, p. 2786.
[14] D. Bulfone et al., "Exploiting Low-gap Beam Position Monitors in Orbit Stabilization Feedback and Feed-Forward Systems at Elettra", J. Japan. Soc. Syn. Rad. Res. 16 (2003) 4.
[15] B. Podobedov et al., "Fast Digital Orbit Feedback Systems at NSLS", PAC'01, Chicago, June 2001, WOPA005, p. 396.
[16] A. Terebilo and T. Straumann, "Fats Global Orbit Feedback System in SPEAR3", EPAC'06, Edinburgh, June 2006, THPCH102, p. 3035.
[17] J. Rowland et al., "Status of the Diamond Fast Orbit Feedback System", ICALEPCS'07, Knoxville, October 2007, RPPA10, p. 535.
[18] M. Lonza et al., "Commissioning of the Elettra Fast Orbit Feedback System", PAC'07, Albuquerque, June 2007, MOPAN024, p. 203.
[19] T. Schilcher et al., "Commissioning and Operation of the SLS Fast Orbit Feedback", EPAC'04, Lucerne, July 2004, THPLT024, p. 2523.
[20] T. Nakatani et al., Rev. Sci. Instrum. 76, 055105 (2005).
[21] L. Hendrickson et al., "Beam-based Feedback Testing and Simulations for the SLC Linac", LINAC'00, Monterey, August 2000, TUC11, p. 515.
[22] T. Himel et al., "Adaptive Cascaded Beam-Based Feedback at the SLC", PAC'93, Washington DC, May 1993, p. 2106.
[23] K. Rehlich, "Status of the FLASH Free Electron Laser Control System", ICALEPCS'07, Knoxville, October 2007, p. 53.
[24] International Linear Collider Reference Design Report, ILC-REPORT-2007-001, August 2007.
[25] V. Schlott et al., "Intra Bunch Train Feedback for the European X-FEL", EPAC'06, Edinburgh, June 2006, THPCH096, p. 3017.
[26] C. Montag et al., "Status of Fast IR Orbit Feedback at RHIC", EPAC'06, Edinburgh, June 2006, MOPLS023, p. 589.
[27] J. Keil et al., "Design of a Local IP Orbit Feedback at HERA-E", EPAC'06, Edinburgh, June 2006, THPCH086, p. 2988.
[28] F. Rouse et al., "Maintaining Micro-Size Beams in Collision at the Interaction Point of the Stanford Linear Collider", PAC'91, San Francisco, May 1991, p. 3222.
[29] Y. Funakoshi et al., "Orbit Feedback System for Maintaining an Optimum Beam Collision", Phys. Rev. Special Topics, Accelerator and Beams, 10, 101001 (2007).
[30] M. C. Ross et al., "Precise System Stabilization at SLC Using Dither Techniques", PAC'93, Washington DC, May 1993, p. 1972.
[31] A. S. Fisher et al., "Commissioning the Fast Luminosity Dither for PEP-II", PAC'07, Albuquerque, June 2007, FRPMS066, p. 4165.
[32] P.N. Burrows et al., "The FONT4 ILC Intra-Train Beam-Based Digital Feedback System Prototype", PAC'07, Albuquerque, June 2007, MOPAN108, p. 416.