REVIEW OF ORBIT CONTROL

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Abstract

Knowledge and control of the closed orbit in particle accelerators are of fundamental importance for the optimization of machine performance. A survey is given of the effects that distort the ideal closed orbit along with methods and technology used in the determination and control of it. Examples of state of art techniques used in the control of the orbit at various facilities are presented.

1 MACHINE PERFORMANCE

Maintaining control of the closed orbit is necessary to maximize the performance of an accelerator. The figures of merit are the luminosity for colliders and the brightness for light sources. In general, control of a light source is more demanding than for a collider simply because of the greater number of source points (bending magnets and Insertion Devices (ID's)) compared to the few interaction points (IP's) of colliders. Two ring colliders are also more demanding than single ring machines because of the different histories of the two beams. Orbit motion affects the figures of merit in two distinct ways: the first is related to the position and angle motion of the beam centroid at the IP's or radiation source points, the second is related to offsets of the beam centroid with respect to the centres of multipole magnets. The second effect, generally associated with feeddown in magnets, gives rise to changes in the optics, dispersion, beam coupling and excitation of resonances that change the beam size and can also lead to changes in the beam lifetime. Light sources striving for the lowest emittances and vertical beam coupling can only take advantage of the optics if the orbit is well controlled. Control of the orbit is mandatory also to ensure proper protection of machine equipment against miss-steered photon beams. Furthermore for machines with small aperture there is also the risk of a reduction of lifetime and loss in injection efficiency. For lepton machines the natural spin polarization is reduced whenever the beam samples horizontal dipole fields, neccesitating a well corrected vertical orbit. In addition induced spurious dispersion also leads to depolarising effects. The polarization is not only useful for experiments but also for the determination of the beam energy [1].

The consequence of transverse orbit stability has to be considered together with the frequency of beam position and angle motion and the time to perform an experiment. For long data acquisition times the jitter of the bunch centroid in phase space can be added in quadrature with the beam emittance and results in an effective increase in the latter. This is true for most experiments performed at synchrotron radiation facilities with data acquisition frequencies below 10 Hz. The effect of slow beam movements is more deleterious.

The requirements on transverse orbit stability are typically specified in terms of tolerated bunch centroid movements as a fraction of the beam size. Most machines have emittances of the order of 10 nmrad and 1% coupling for lepton machines. Depending on the betatron function at the IP or ID, beam sizes are approximately 10 microns or less. The usual 10% (or less) beam size stability requirement therefore implies orbit control at the sub-micron level. This in turn poses very challenging requirements on the global stability of the accelerator.

Controlling the closed orbit involves more than simple correction using steerer magnets, it fundamentally also requires the suppression of disturbances through careful electrical, mechanical and civil engineering.

In the following sections broad statements will be made based on information gathered from approximately 35 circular accelerator facilities. Given the limited amount of space it is unfortunatley impossible to acknowledge all sources of information or give more than a few details.

2 SOURCES OF DISTURBANCE AND PASSIVE CONTROL

We can categorize disturbances to the closed orbit on various time scales. From months to years ground settling [2], seasonal changes and ground diffusion [3] result in changes in the position of magnets. Dipole rolls about the logitudinal axis and transverse displacements of multipole magnets have a strong influence on the closed orbit. Frequent surveys and realignments are therefore needed. In general surveys are done once or twice a year whereas realignment is performed every two to four years. Magnets are typically aligned to a precision of 0.1 mm in position and 0.2 to 0.5 mrad in angle. The time to realign, which can range from a day to several weeks, is also of importance especially for light sources which operate for 6 to 7 thousand hours/year allowing little time for shutdown work. An advanced alignment system at the ESRF uses a hydrostatic leveling system (HLS) in the vertical plane which permits alignment with beam in a few hours [4]. This technique has also the advantage of performing the alignment under operating conditions thereby minimizing thermal effects and alignment cycles. The SLS [5] is deciding on the use of an HLS or ultrasonic system in the vertical plane along with a wire positioning system and "train links" between girders or an optical system in horizontal plane.

On time scales of day to weeks: tides, diurnal variations, rivers, water-tables [6,7], rain, synchrotron radiation, refills and start-up, local machinery, filling patterns, monitor motion and drifts in electronics all contribute to orbit motion or loss or orbit control.

Synchrotron radiation is particularly troublesome since only a small fraction of the total emitted power is used in experiments. The remaining power has to be absorbed and dissipated by absorbers in the vacuum chamber. Notwithstanding significant design and cooling of chambers most lepton machines suffer from thermal variations after refills [8]. The effect can manifest itself in movement of the chamber and monitors. Monitor movement is particularly harmful if these are used in local correction schemes. Global correction of the orbit using many monitors has then the advantage of minimising monitor errors and correcting only "physical" disturbances [9]. A possible solution to minimise the thermal drifts due to synchrotron radiation is to adopt a top-up mode of operation [10]. Other common forms of thermal variation arise from machine restarts. Closed orbit settling of a few hours to several days is commonly observed. As already stated light sources operate for several thousand hours per year and closed orbit settling times may represent (depending on operational procedures) a significant loss of performance. Although these orbit drifts can be corrected, the correction is again only effective if the monitors themselves are immune to thermal variations. At SPring-8 magnets are not powered down during short shutdowns to avoid the above mentioned effects [11]. Different operating modes also affect the closed orbit. Observations at LEP reveal thermal movement of the IP quadrupoles as a function of machine energy. The effect is compensated by a feedback system using information from an HLS system on the magnet supports [12]. At HERA the support system of the IP quadrupoles are continuously monitored (stretched wire and HLS) and temperature regulated [24].

On shorter time scales, hours and less, the closed orbit is affected by ground vibrations [13], power supplies, injectors, insertion devices, refrigerators/compressors and air conditioning. Ground vibrations are a common source of orbit motion. Power spectral densities (PSD's) [3] as a function of frequency at various laboratories all show three general features: a broad peak around 0.07 to 0.2 Hz due to ambient seismic noise arising from ocean tides, a region from 1 to 100 Hz dominated by cultural noise and a rapid decrease in the PSD at higher frequencies. To separate magnets from the ground some form of support system is used. The most common form of support is the girder. It allows the grouping and pre-alignment of individual magnets with subsequent ease in the alignment of the entire machine [14]. However, special care has to be taken in the design and construction of the girder to avoid vibrational resonances of the structure. For existing machines the first eigenfrequencies are usually around 5 to 20 Hz. Future machines are making extensive use of finite element methods in the design of pedestals and girders to have the first resonant frequency as high as possible e.g., 44 and 60 Hz for the SLS and SOLEIL respectively [15, 16].

An additional technique to suppress the amplification of girder resonances is the use of sandwiches of visco-elastic materials and steel plates. The sandwiches placed between pedestals and girders can provide up to a factor of 200 in the reduction of a resonance [17, 18]. A six layer structure is being commissioned at the ESRF [19].

The thermal stability of utilities and general services also has a strong impact on the stability of the orbit. There is an increasing tendency to improve the temperature stabilization of magnet cooling and ambient tunnel temperature [11, 20, 21], which for most machines are approximately ±1.5 and ±2.5°C respectively. Improvements are being made to have ±0.1 and ±0.2°C. Also of importance is good temperature regulation of service galleries which affects the performance of electronics and power supplies.

3 BEAM POSITION MONITORING

The final quality of orbit control is intimately related to the accuracy and resolution of the beam monitoring system. Monitors are generally placed close to the source of orbit distortion and close to the sources of photons or collision points. The vast majority of machines have rf-beam position monitors (BPM's) close to quadrupoles, although a few (APS, SPring-8 and the SLS) have them close to the strong sextupoles found in third generation light sources. The accuracy of a reading is determined by the mechanical and electrical calibration of the monitor as it is also by the current, bunch pattern, button processing electronics, temperature and for multiplexed systems longitudinal multi-bunch instabilities [22].

To minimize mechanical movement the method of fixing the monitor with respect to the magnet centre line is important. Three methods of fixing the monitor can be found: floating with the chamber, fixed to a nearby magnet and fixed to the girder. A monitor floating with the chamber may suffer from thermal movement of the chamber, those fixed to magnets may transmit mechanical movement to the magnet if not isolated from the chamber by bellows. Monitors fixed to girders should ideally also be isolated from the chamber by bellows. This option is being chosen for SOLEIL whilst the SLS has chosen to fix the BPM to the girder and is considering to monitor the position by optical means [5].

Gain drifts and non-linearities show up as position dependence on the current. Multiplexed systems are less susceptible to these effects, however, automatic gain controls can cause reading errors when switching.

Knowledge of the offset of a BPM with respect to a nearby magnet results in improved control of the orbit and feeddown effects. Beam based alignment (BBA) techniques [23] can allow determination of the offset to 20 microns [24], whereas conventional techniques (electrical, optical and mechanical) give accuracies of ~100 microns.

calibration by BBA has the advantage of determining the overall offset including both electrical and mechanical terms. The technique can be applied to both quadrupoles and sextupoles [25]. For sextupoles the orbit response can be replaced by the tune response [11]. BBA techniques require the possibility of changing the focusing strength of quadrupoles [26]. This can be done by using dedicated power-supplies or shunts on individual magnets when they are powered as a family. K-modulation, a technique used at LEP [27], can determine the offsets of 16 BPM's parasitically during physics runs. In this way significant improvement in the polarisation has been obtained.

The resolution of rf-BPM's can be broadly associated with the sampling speed and ultimately with the analog to digital converters. Multiplexed systems are slower than parallel processing systems but have the advantage of using common electronics and reduced costs. This option is the favorite with many laboratories. Parallel processing of button signals, however, has a wider bandwidth. There is a general tendency for may laboratories to use both systems. Typical resolutions are around 2-3 microns at a few hundred Hertz data acquisition. Systems are being developed, both multiplexed and parallel processing which will give a few microns or less resolution at 1 kHz [28, 29] and sub-micron resolution at lower frequencies (0.2 μm at 100 Hz for SOLEIL [16]).

Another common monitor found in light sources is the photon beam position monitor (pBPM) which can provide sub-micron resolution. These monitors work well with only bending magnet radiation but suffer from contamination from the radiation of upstream and downstream magnets when used with photon beams from ID's. To circumvent this effect, electronics have and are being developed to measure the energy of the photo-electrons rather than the current from a blade [30, 31]. Alternatively the undulator, pBPM's and beamline can be moved radially outwards from the centre of the ring, thereby eliminating the bending magnet radiation [32].

4 CORRECTION ALGORITHMS AND TECHNIQUES

Performing an orbit correction [33] entails reading the orbit position **u** at a set of BPM's and applying a set of corrector settings θ to obtain readings of desired values $\mathbf{u}_t$. The vector of final values $\mathbf{u}_t$ is usually the "golden orbit", or that orbit which gives the best machine performance. We note that this orbit is generally not the best orbit in terms of beam position in the centre of multipole magnets. The relation between $\mathbf{u}_t$ and θ is simply given by: $\mathbf{u}_t=\mathbf{R}\theta+\mathbf{u}$. The response matrix **R** is a function of the betatron function and phase advances between a monitor and corrector magnet. Either the model or measured response matrix can be used in the correction. The elements of the measured response matrix are simply given by the orbit difference at a BPM for a unit setting of a corrector magnet. Again from information of our representative set of laboratories, approximately half use measured values. The time to measure **R**, which can range from minutes to hours, depends on the number of monitors and correctors and the accuracy of the measurement. The choice to use either the model or measured **R** depends on the efficiency desired for the correction. In general orbit feedback systems utilize measured **R**. To have the best correction requires an adequate knowledge of the orbit in betatron phase space, i.e., sufficient monitors for a good mapping. In addition an adequate distribution of correctors in phase space is also needed. As an example at KEKB there are 9 to 10 BPM's and 18 to 20 correctors per betatron wavelength [34]. Costs, space and the type of lattice strongly influence the distribution. Analysis by simulations can help in deciding the minimum requirements [35].

Since **R** is usually a rectangular matrix, straight forward matrix inversion cannot be used. Differences between the model and actual optics, errors in measuring **R** or the inclusion of ineffectively placed monitors or correctors in betatron phase space can give singular or ill-conditioned response matrices. Leading to overly large corrector settings or the impossibility of performing a formal inversion. Information from approximately thirty-five laboratories shows that the most commonly used correction algorithms are Singular Value Decomposition (SVD) (50%) [36], Micado ("best corrector method") (35%) [37], harmonic correction (8%) [38]. Local orbit bumps are universal. SVD over the past ten years has seen a rapid growth in its use. The method is a very robust decomposition of the response matrix that permits the exclusion of singular values. The matrices of the decomposition $\mathbf{R}=\mathbf{U}\mathbf{W}\mathbf{V}^T$ have the following properties: **U** is column normal and transforms the BPM readings, **V** is square orthonormal "eigenvector" matrix and transforms the correctors settings and **W** is diagonal. The transformations result in a one-to-one mapping of the transformed readings and corrector settings weighted by the diagonal elements of **W**. The required corrector settings are a linear superposition of the eigenvectors. Small eigenvalues giving large correctors settings, correspond to nearly singular values are discarded, only the most effective eigenvalues/vectors are used. Depending on the distribution of errors that generates the closed orbit distortion the use of corrector eigenvectors leads to distributions of corrector settings that either collapse to localized bumps/single correctors or result in distributions having the same number of nodes as the machine tune [39, 50]. In this sense the method mimics both the harmonic correction method and the best corrector method/bump method (see below).

The following observations can be made: for more monitors than correctors the method results in a minimization of the monitor errors and a smoothing of the orbit, using more correctors than monitors results in an exact correction at the monitors and a minimization of the corrector strengths. Since orthonormal eigenvectors are being used we can choose different vectors to perform different tasks, i.e., decoupling of different correction or feedback systems [40]. SVD can be used to solve generalized matrices: the correction of the orbit mean by means of rf changes can be incorporated as is done at the ESRF. Additionally the simultaneous correction of the spurious dispersion and orbit may be performed by generalizing the method to include the response matrix of the dispersion weighted by an appropriate factor [41].

The second most common correction technique is the Micado method. The technique has the advantage of finding locations of strong orbit distortion and using few correctors. The harmonic method decomposes the measured orbit into a Fourier series in betatron phase. Since the closed orbit follows betatron motion the distortion is well described by a few harmonics close to the integer part of the machine tune. Correcting for these harmonics results in weak corrector settings.

Closed orbit bumps are universal and are utilized to perform an orbit correction over limited parts of the machine. Two correctors are required to localize the bump. Additional correctors allow the control of angle and/or position at specified locations. Combinations of overlapping bumps can be used to globally correct the orbit. SVD may be used to find the settings by using those eigenvectors of the response matrix $\mathbf{R_b}$ that connects the bump correctors to monitors outside the bump. The eigenvectors of the singular values (it can be shown that $\mathbf{R_b}^T\mathbf{R_b}$ is singular) are then used to determine the response matrix for the monitors used in the bump (either rf-BPM's or pBPM's). This has the advantage that the bump can be calibrated without disturbing the rest of the machine [42]. At light sources there is a general trend towards global rather than local correction. This is a result of minimizing the monitor errors and uncertainties and additionally to less costly solutions.

The decoupling of orbit correction systems, local/global or DC/AC global, can be performed in various ways: through frequency separation [APS, ESRF], the use of different eigenvectors for orthogonal loops [SPEAR], via the general incorporation of local and global correction in a unified response matrix [APS] or through the design of communicating loops [NSLS].

Feedfoward techniques are applied to correct known orbit disturbances. Essentially, lookup tables are generated that contain corrector settings as a function of some machine parameter. The method is used in energy ramps and IP beta-squeezes. Light sources routinely use this method for the correction of residual field errors from insertion devices. Ring corrector magnets, dedicated coils or rotating magnetic blocks are powered as a function of gap change. The method can also be used to compensate rapidly changing fields (100Hz) used in ID's for the production of polarised radiation [43].

5 ORBIT CONTROL

Most machines have some form of slow (DC) orbit correction, which is either performed by the operator or some high level computer. The frequency of correction ranges from once a day to several times a minute. Control theory is always applicable, at the lower frequencies the correction is essentially proportional to the reading. As the frequency increases dynamical effects have to be taken into consideration: response of the magnet and power supply, eddy current effects, delays in data acquisition and so on. In this case some form of PID controller is necessary [44]. Both analog and digital feedback systems are used. Simple analog systems are usually faster and cheaper to implement, however, digital systems are rapidly evolving (higher sampling rates, shorter processing delays). The main advantage of digital over analog is flexibility, reproducibility, the inclusion of system diagnostics, the minimisation of drift and sensitivity to temperature changes, the transmission of data from/to a large number of BPMs/corrector power supplies in a reliable way even over long distance, the compensation of eddy-current effects and the implementation of "modern" control techniques.

At the SRS [45] the vertical local orbit correction scheme has been upgraded to a global system because of limitations in the number of corrector magnets available for the correction at all beamlines. The system operating every 30s, uses SVD and a measured response matrix. The position signals are provided by Tungsten pBPM's in the beamlines. Drifts of ~100 microns over 2 hours are compensated to a few microns level. The system handles the closing of a beam port by reloading a new **R** matrix.

Many light source laboratories are developing or have in operation fast global orbit feedback systems. An interesting simultaneous use of both analog and digital fast feedback systems is performed at the NSLS [46]. The system uses 16 electron BPM's and 22 correctors, an SVD is made of the measured response matrix and the first 8 eigenvectors used for the analog feedback. An SVD is subsequently performed on the measured response matrix with the analog feedback on and the top 10 eigenvectors used in the digital feedback. At the ESRF a fast vertical global feedback system using high resolution electron BPM's position about the ID straight section is being commissioned. The system utilizes two consecutive ID straights followed by a gap of six for a total of 16 monitors and correctors [47]. The Photon Factory is also commissioning a fast global system [48], as is the SRRC [49] and Super-ACO [16]. Both the ALS and SPring-8 are planning to implement global systems in the future.

Significant progress in the use of fast global feedback has been made at the APS [50]. The system (1-2kHz) uses one corrector per sector and 160 out of 360 BPM's, SVD is performed on the response matrix and no singular values are removed. The system has been in operation since June 1997, the loops can be opened and closed with no impact on stored beam, it operates during injection and at the time of writing has caused only one beam loss since that date. The availability has also been 99% since handover to operations.

With regard to fast local feedback [54], systems are in operation at SPEAR-II, SRRC, ESRF. BESSY-II is planning to commission their system (100 Hz) using electron BPM's in the autumn this year. Significant work has also been performed at Elettra [42], however, the work has been suspended pending developments on new monitors [31, 51]. For colliders, local feedback systems can be implemented using information from beam-beam deflections [52] or the coupling of oscillations from the two beams [53].

6 ACKNOWLEDGMENTS

The talk and this paper is the result of a great deal of effort and information given to me by many people, all of whom I am very grateful to. I can only apologise for not being able to individually acknowledge their contribution.

REFERENCES

[1] B. Dehning, et al., "Calibration at LEP using nuclear magnetic resonance probes", This Conference.
C. Steier, et al., "Correction of Depolarising Resonances in ELSA", PAC, (1997).
[2] J. Poole, et al., "The effects of LHC civil engineering on the SPS and LEP machines" This Conference.
[3] V. D. Shiltsev, EPAC, (1996), 32.
[4] D. Roux, in Proc IV Intl. Workshop. On Accel. Align., KEK Proc, 95-12, (1995).
[5] A. Wrulich, SLS, Private Communication
[6] R. Assmann, et al., CERN-EP/98-40, (1998).
[7] H. Sato, et al., "Floor level fluctuation of the KEK-PS tunnel", 1st. Asian Part. Accel. Conf., (1998).
[8] J. Safranek et al., PAC, (1995), 2711.
[9] G. Decker, "Performance of the Advanced Photon Source", PAC, (1997).
[10] R.P.Walker, "Overview of Synchrotron Radiation and FEL Projects", This Conference.
[11] H. Tanaka, SPring-8, Private Communication
[12] F. Tecker, et al., "Closed orbit feedback from low beta quadrupole movements at LEP", PAC, (1997).
[13] L. Zhang, EPAC, (1996), 1359.
[14] H. Tanaka, NIM, A313, (1992), 529.
[15] L. Rivkin, et al., "SLS lattice finalisation and magnet girder design", This Conference.
[16] A. Nadji, SOLEIL Project, Private Communication.
[17] D. Mangra, et al., Rev. Sci. Instrum., 67, (1996)
[18] J. Feikes, "Measurements of ground and girder vibrations at BESSY II", This Conference.
[19] L. Zhang, ESRF, Private Communication.
[20] R. Keller, et al., "Orbit stability of the ALS storage ring", PAC, (1997).
[21] J. R. Chen, et al., "The correlation between the beam orbit stability and the utilities at SRRC", This Conference.
[22] R.Nagaoka and A. Wrulich, EPAC, (1996), 316.
[23] G. Portmann and D. Robin, "Beam-Based Alignment of C-Shaped Quadrupole Magnets", This Conference.
[24] F. Willeke, HERA, Private Communication.
[25] M. Kikuchi et al., PAC, (1995), 603.
[26] S.A. Griffiths et al., "Design and Testing of a Low Cost Modulating Current System for Determination of SRS Quadrupole Misalignment", This Conference.
[27] B. Dehning et al., "Dynamic Beam Based Calibration of Beam Position Monitors", This Conference.
[28] V. Schlott and R. Ursic, "Electron Beam Diagnostics for the Swiss Light Source", This Conference.
[29] J.Sebek et al., DIPAC, (1997), 94
[30] K. Holldack, BESSY-II, Private Communication and BESSY Annual Report, (1997), 515
[31] A. Galimberti and C. Scafuri, This Conference.
[32] G. Decker, "Fundamental Limits on Beam Stability at the APS", Beam Instrumentation Workshop, (1998).
[33] E. Bozoki et al., Eds., "Orbit Correction and Analysis in Circular Accelerators", AIP Conf. Proc. 315 (1994).
[34] H. Fukama, KEK-B, Private Communication
[35] A. Nadji and P. Nghiem, EPAC, (1996), 673.
[36] W.H.Press et al., "Numerical Recipies", Cambridge University Press, (1998).
[37] B. Autin and Y. Marti, CERN ISR MA/73-17 (1973).
[38] E. Gianfelice and R. Giannini, CERN/PS 85-42 (lEA), (1985).
[39] Y. Chung et al., PAC, (1993), 2275.
[40] J. Corbett et al., PAC, (1994), 1583.
[41] R. Nagaoka, EPAC, (1996), 980.
[42] C.J. Bocchetta et al., DIPAC, (1997), 61.
[43] O. Shing and S. Krinsky, "Orbit Compensation for the Time-Varying Elliptically Polarised Wiggler with Switching Frequency at 100 Hz", PAC, (1997).
[44] T. Himel, "Feedback: Theory and Acclerator Application", SLAC-PUB-7398, (1997)
[45] S.L. Smith, "Recent Improvements in Vertical Orbit Feedback at the Daresbury SRS", This Conference.
[46] O. Singh et al., "Orbit Feedback at the NSLS", Submitted to NIM, BNL-65093, (1998).
[47] J.M. Koch et al., "A Fast Global Feedback System to Correct the Beam Position Deviation in the ESRF Storage Ring", This Conference.
[48] T. Obina, "Global Feedback System for Photon Factory Storage Ring", 1st. Asian Part. Accel. Conf., (1998).
[49] C.H.Kuo, et al., "Digital global orbit feedback system developing in SRRC", PAC, (1997).
[50] J.A. Carwardine and F.R. Lenkszus, "Real-Time Orbit Feedback at the APS", Beam Instrumentation Workshop, (1998).
[51] R. DeMonte and M. Ferianis, "New Features of the Elettra BPM System", This Conference.
[52] Y. Funakoshi, et al., PAC, (1995), 2521
[53] O. Berrig, et al., "Real-time monitoring of beam-beam modes at LEP", This Conference.
[54] C.H. Kuo, "Development of Local Orbit Feedback for Taiwan Light Source", This Conference.