DESIGN CONSIDERATIONS FOR THE ELETTRA BEAM POSITION FEEDBACK SYSTEMS

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Abstract

The "natural" stability of the photon beams provided by a synchrotron radiation facility is generally far off the stringent requirements of most users. For ELETTRA, a third generation light source in construction in Trieste (Italy), two position feedback systems are foreseen in order to suppress this kind of problem. A local feedback system dedicated to photon beam lines is discussed; an other feedback, correcting globally the closed orbit of the machine, is described in more detail. The latter uses the beam position monitor system of the machine and suppresses the main harmonics of the closed orbit by applying the appropriate current to a few corrector magnets. A digital approach, should allow an easy optimization of the system by leaving open the choice of the monitors, correctors, and harmonics to correct. The principal difficulty is to provide the high calculation speed and data transmission rate for correcting vibrations up to 50 Hz.

Introduction

The stability of the photon beams is one of the most critical parameters for the high brilliance third generation synchrotron radiation sources [1]. Many user experiments are sensitive to small changes in the photon beam intensity that can be induced by movements of only a fraction of the beam dimensions. The main disturbing sources affecting beam stability are: power supply ripples and drift [2]; cooling water or air temperature changes deforming magnets and girders; ground vibrations [3] induced by seismic motion, compressors, etc., coupled through the quadrupole magnet supports. Spectra of beam fluctuations, measured in many facilities [4-7], show most of the components in the 0 to 100 Hz range including a component at the frequency of the mains (50 or 60 Hz).

Considering the beam sizes listed in table 1, the particle beam must be stabilized within a few µm. Different feedback system types will equip ELETTRA for this purpose: local feedback, closed orbit feedback. They will be first implemented for the correction in the vertical plane and later on in the horizontal one.

Table 2 shows the domain of application of each type of feedback. The local feedback is the most effective system: it corrects the perturbations taking place in both the machine and the photon beamline, and can reduce movements up to two orders of magnitude. However, we cannot equip both an Insertion Device (ID) and a bending magnet beamline in the same achromat of ELETTRA. Local feedback systems will be only installed on the ID beam lines. For facilities with many beamlines, a closed orbit feedback acting on the electron orbit as a whole is very attractive; using a relatively small number of dipole correctors, it can damp drifts and vibrations of the beam by a factor of 3 to 5. The bending magnet beamlines will mainly take advantage of that feedback which will however enhance the quality of all beamlines.

The closed orbit feedback needs to be defined as early as possible in the design of the machine because it affects extensively many parts of that design: Beam Position Monitor (BPM) system and its control, corrector magnets and their power supplies.

Table 1: ELETTRA parameters at 1.5 GeV.

Circumference	259.2	m
Vert. Betatron Tune	8.2	
Horiz. Betatron Tune	14.3	
Emittance	4 10^{-9}	π·m·rad
Insertion Device source:		
Vert. size with 10% coupling	32	µm
Horiz. size	181	µm
Bending magnet source (3.5°):		
Vert. size with 10% coupling	60	µm
Horiz. size	100	µm

Table 2: Feedback systems and their domain of application.

Feedback type	Photon source	Correction domain	Frequency range
Local	ID	e^- & Beamline	0 - 50 Hz
Closed orbit	Bending	e^-	0 - 50 Hz

Local Feedback System

Many local feedback systems have been developped for other machines [4-7]. For ELETTRA, each local feedback comprises:

- Two photon-beam-position monitors that measure the vertical deviation in angle and position of the beam with respect to those of the reference orbit.
- A set of four dipole magnets that create locally the beam bumps in angle and position that are of opposite sign and same amplitude as the beam perturbation.
- A two-input-four-output analog circuit which gives the proper corrections from the BPM informations.

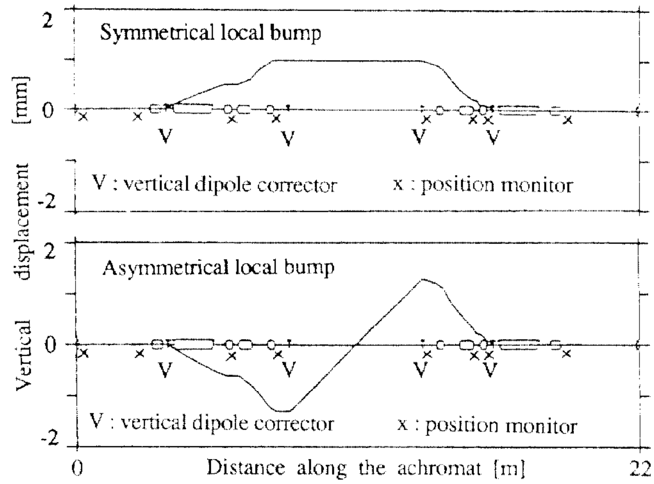

Figure 1: Local feedback correction bump.

The shape of the bumps and the location of the steerers [8] are shown in figure 1. An extensive study of the beam stability [9] when eleven loops equip all IDs show that the individual bump residuals around the machine must be kept below one eleventh of their full strength in order to keep the whole system stable. The crosstalk between loops may be contained easily at low frequencies, but at higher frequencies the instantaneous strengths of the four magnets must stay proportional and it becomes important to match their individual phase and gain response; the same comment applies to the other elements of the loop such as power supplies, photon monitors, analog circuit, and eddy current effect in the four pieces of vacuum chamber.

The local bumps of figure 1 should not extend further and cover the bending magnet beamline because the compensation of a mechanical vibration in the ID beamline, corrected by shaking the beam in opposite direction, would generate perturbations on the bending magnet beamline. In addition to that, the present scheme leaves only 4 BPMs out of 8 in an achromat to monitor the closed orbit feedback.

The open loop at low signals (small beam perturbations) can have a cut-off frequency quite high: an experimental steerer with its power supply [13] and a piece of ELETTRA's vacuum chamber showed that only 5° of phase rotation at 100 Hz can be achieved. However, non linear saturating effects appear when the speed of the beam deviation increases above a limit which is depending on the power supply maximum voltage. For ELETTRA, this limit has been set by specifying the bump strength at 50 Hz $K_{(F)}$, to 2% of the maximum

DC bump strength; that will correct up to ≈ 30 μm and 12 μrad of beam oscillation at that frequency. The product $K_{(F)}.F$ does not actually depend on the frequency, thus the above specification defines a constant that will now help to find a relation for optimizing the magnet-power-supply system. By definition $K_{(F)} = I_{(F)} / I_{max}$; $I_{(F)}$ is the maximum peak current at the frequency F and I_{max} the DC current in the corrector corresponding to its maximum strength. At high frequencies the load impedance is mainly inductive, and the current delivered by the power supply must satisfy the relation:

$$I_{(F)} \leq (V_{max} - V_{DC}) / 2\pi \cdot L \cdot F \qquad (1)$$

where V_{max} is its maximum voltage, V_{DC} the DC voltage of the power supply at its maximum strength, and L the inductor of the magnet. Replacing $I_{(F)}$ by its value in equation (1), we obtain:

$$\frac{V_{max} - V_{DC}}{2\pi \cdot L \cdot I_{max}} \geq K_{(F)} \cdot F \qquad (2)$$

where the right hand side is a constant; the parameters on the left hand side are related to the magnet-power-supply system; they will be optimized for a minimum cost. If the amplitude of the vibrations exceeds the limit values, the power supply of the stronger corrector saturates and unbalances the bump; that increases the bump residuals around the ring and the beam can be lost if many local feedback loops are working simultaneously.

Closed Orbit Feedback System

The closed orbit feedback brings back the beam to its reference orbit. After reading the actual closed orbit of the particle beam, the system calculates the difference with the reference orbit; the spectrum of that difference has the strongest harmonics near the betatron tune [10]. Eliminating two or three of these harmonics, by a proper set of dipole correctors, largely reduces the beam deviation. With high acquisition and calculation rates, this system should suppress relatively high frequency movements. A 4-monitor-4-dipole corrector closed orbit feedback system using relatively simple analog electronics is operating at the VUV ring of the NSLS [11]. The system foreseen for ELETTRA , which has high betatron tune values, will need a large number of BPMs and the possibility of changing easily their configuration to another one; only a digital system can provide this flexibility.

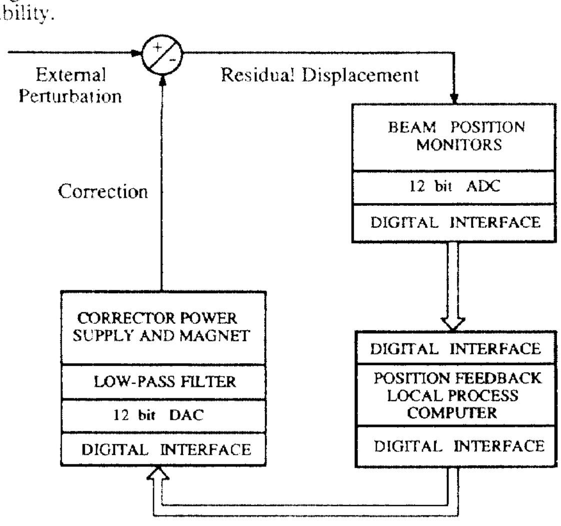

Figure 2: Block diagram of the closed orbit feedback system.

The block diagram of the hardware involved in the closed orbit feedback is shown in figure 2. The closed orbit data measured by the BPM system are transferred through a fast digital interface to a central computer called Position Feedback Local Process Computer (PFLPC) [12] which analyses the harmonic content and computes the correction kicks. Using the same model of fast digital interface, the correction kick values are transmitted to the electronics controlling the corrector power supplies, then converted by 12 bit Digital to Analog Converters (DAC) and via the power supplies and magnets are finally applied to the particle beam. A possible transfer function for the loop is represented in figure 3.

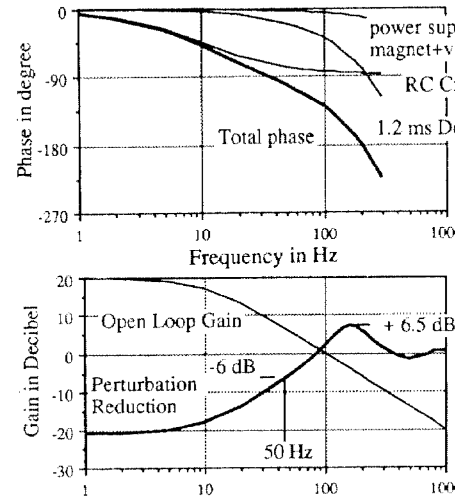

Figure 3: Closed orbit feedback loop transfer function.

To damp the 50 Hz beam movements by a factor of 2, the cut-off frequency of the feedback loop should be about 100 Hz. A low pass filter that has a 10 Hz bandwidth and a gain sufficient to adjust the DC gain of the open loop to 20 dB, assures the stability of the closed loop. The total phase rotation results from three distinct contributions: the phase response of the set magnet+power supply+vacuum chamber, the phase response of the low pass filter and the time delay from the acquisition of the BPM data until the power supply DAC is set with the correction kick value. The vacuum chamber is in 2 mm thick stainless steel and the attenuation due to the eddy currents is small up to 1 kHz; however a non negligible phase rotation (about 3° at 100 Hz) takes place. A test [13] done with a power supply and a piece of vacuum chamber mounted into a steerer magnet has shown that a phase rotation as small as 5° between the DAC output and the magnetic field inside the chamber can be achieved. The low-pass filter guarantees the loop stability with its gain frequency response, but introduces a large phase rotation: 84° with the example shown in figure 3. Then the remaining phase ϕ_D that defines the maximum delay τ of the low power chain at the frequency F = 100 Hz is about 46° (0.8 rad). The classical relation:

$$\tau = \frac{\phi_D}{2\pi F} \cong 1200 \ \mu s$$

with ϕ_D in radians, gives the total delay budget which puts tight requirements for the BPM system and the digital control electronics. The maximum time delay for each item is specified as follows:

- 410 μs for measuring the x and y values and transferring them to the fast digital interface.
- 120 μs for the transmission of the x, y coordinates to the PFLPC.
- 520 μs for the harmonic analysis and computation of the kick values.
- 120 μs for the transmission of the correction kick values from the PFLPC to the power supply fast digital interface.
- 30 μs for the setting of the power supply DAC with the correction kick data.

All the electronics is based on the VME [14] standard bus. The fast digital interface must allow the communication of all the feedback loop data which are distributed around the ring, with the central PFLPC; the main difficulty is to provide a high transmission rate (about 500 kbytes/s) at long distances (up to 150 m). Two fast digital interface test circuits [15], connected through an 8 bit bus, have shown transmission rates up to 1 Mbytes/s at 90 m distance, using a low quality flat cable. The performance should even be better with multiconductor shielded twisted-pair cable.

The short time (520 μs) left to the PFLPC for the computations requires a very high processing speed which will be provided by a Digital Signal Processor (DSP) board. That board brings in addition the advantage of user programmability. To take advantage of possible DSP improvements in the future, the PFLPC will have a modular open architecture.

The closed orbit feedback requires top performance features from the BPM system [16]: a good BPM support for holding the monitor into a stable position (± 10 μm), taking into account the possible temperature changes during a few hours; a very low beam current dependence (≤ 10 μm) of the electronic detector; a fluctuation of the measurement smaller than 5 μm, concurrently with a speed of about 2400 orbit/s. The three last requirements have been met in the lab with a test electronics. The number of BPMs installed on the storage ring is 96. When the local and the closed orbit feedback systems are operating simultaneously, the maximum number of BPMs available for the latter is 48.

Lumped horizontal and vertical correctors, separately powered, will be implemented for ELETTRA; the power supplies will use bipolar linear transistor regulators.

Simulation

A simple simulation helped estimating the efficiency of the correction algorithm. Let us simulate a kick applied by one of the vertical dipole correctors. After computing the perturbed closed orbit, we can expand it into a Fourier series as follows:

$$\mu = a_0 + \sum_{n=1}^{\infty} a_n \cos(n\phi) + b_n \sin(n\phi)$$

where μ, representative of the vertical displacement, and the phase φ are the Courant-Snyder [10] variables. The spectrum in amplitude, defined by:

$$|c_n| = \frac{1}{2}\sqrt{a_n^2 + b_n^2}$$

is shown in figure 4a. We see that the strongest harmonics are close to the betatron tune value $Q_v = 8.2$. The closed orbit is actually measured only where the BPMs are located. Let us choose a set of 48 BPMs and calculate the Fourier coefficients a_n, b_n for n=7, 8, 9 which minimize the following expression [17]:

$$\sum_{i=1}^{48}\left[\mu_i - \sum_{n=7}^{9} a_n \cos(n\phi_i) + b_n \sin(n\phi_i)\right]^2$$

where μ_i and ϕ_i are the μ and φ values at the various BPM locations. The amplitudes $|c_n|$ are in good agreement with the orbit spectrum calculated above (figure 4a).

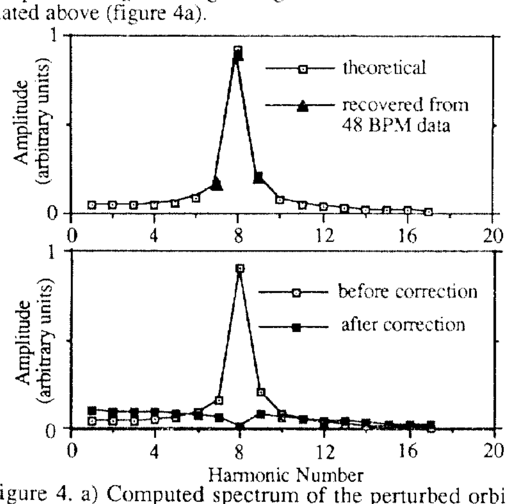

Figure 4. a) Computed spectrum of the perturbed orbit due to a steerer kick ($Q_v = 8.2$); comparison with the 7th, 8th and 9th harmonic amplitudes recovered from 48 BPM data. b) Comparison between the orbit spectra before and after harmonic correction.

Different configurations, consisting in pairs of vertical correctors, have been simulated to cancel the eighth harmonic of the perturbed closed orbit. The resulting corrected orbit depends on the relative positions of the perturbation and correction kicks. As an example, figure 4b shows the comparison between the Fourier spectra of the orbit, before and after the correction.

Conclusion

Two complementary types of position feedback system are foreseen for ELETTRA. The closed orbit feedback will benefit mainly the bending magnet beamlines, but will improve the electron beam stability around the whole ring; as a consequence, the local feedback will need less strength and will act mainly against disturbances arising along the photon beamline. The local correction bumps should be kept as short as possible to leave enough BPMs for the closed orbit feedback to operate.

A digital implementation of the closed orbit feedback will allow the use of a large number of BPMs; moreover, the system will be easily reconfigurable changing the chosen set of BPMs and dipole correctors. The use of programmable DSP chips for the execution of the correction algorithms should assure the requested processing speed, and enhance the flexibility of the system.

The partial tests done in the laboratory on models of some components (acquisition part of the BPM system, fast digital interface, dipole corrector with power supply and vacuum chamber) have been encouraging. The estimated computing time (BPM system processor, PFLPC and DSP) needs confirmation.

Acknowledgements

The authors would like to thank C. J. Bocchetta for the helpful discussions and F. Cavazzoni for his collaboration in the design of the fast digital interface board.

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