解説

Exploiting Low-Gap Beam Position Monitors in Orbit Stabilization Feedback and Feed-Forward Systems at ELETTRA

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Abstract

Two low-gap electron Beam Position Monitors (BPMs) equipped with digital detector electronics have been installed either side of an Insertion Device (ID) long straight section at ELETTRA. The new BPMs have been integrated in a fast local orbit feedback system that stabilizes the electron beam orbit at the center of the ID. They also provide the basic measurements that are used by a feed-forward correction system compensating for the orbit distortion produced by an Electromagnetic Elliptical Wiggler (EEW) operated at high switching frequencies (up to 100 Hz) of the horizontal field. The main results achieved are presented.

1. Introduction

One of the main goals of the last generation of synchrotron light sources is the stability of the electron beam inside the Insertion Devices (IDs). The reduced operational coupling and emittance of the machines together with recent progress in experimental techniques and data acquisition rates necessitate beam stability in the sub-micron range over frequencies up to several tens of Hz. In order to be able to meet such specifications a new generation of electron Beam Position Monitors (BPM) is being installed at ELETTRA and used in feedback and feed-forward systems for orbit stabilization. Two examples are presented: a fast local orbit feedback and a feed-forward system for the compensation of the orbit distortion created by an Electromagnetic Elliptical Wiggler (EEW) that works at relatively high switching frequencies of the horizontal field.

2. Low-gap Beam Position Monitors

As part of a general ongoing upgrade program, two new type electron BPMs[1] (nominated ‘low-gap’ BPMs) located either side of the ID have been installed in the long straight section 2 of ELETTRA. These four-button BPMs are based on a new mechanical design of the sensor, which takes full advantage of the 14 mm low-gap ID chamber and is de-coupled from the rest of the vacuum chamber by bellows. Residual mechanical drifts are monitored with respect to a reference column made of carbon fibre and taken into account in the final electron beam position reading. The detector electronics of a low-gap BPM consists of an analog Front-End plus a four-channel Digital Receiver VME board that provides the digitized values of the signal for each of the BPM buttons.

3. The Local Orbit Feedback System

The aim of the fast Local Orbit Feedback (LOF) system is to stabilize the electron beam position and angle at the corresponding ID center without affecting the rest of the orbit. The most important noise sources considered are temperature changes producing drifts on different machine equipment, closed orbit distortions generated by ID operation, mechanically and electrically driven vibrations up to some tens of Hz, which include persistent periodic oscillations derived from the mains at 50 Hz and its harmonics.

3.1 System Overview

The layout of the LOF system is shown in **Fig. 1**. Using the two low-gap BPMs and four corrector magnets as sensors and actuators respectively, the LOF creates a local orbit bump that corrects the position and angle of the electron beam at the ID centre with no distortion to the rest of the orbit. The same ELETTRA standard corrector magnets normally used for orbit corrections are also employed by the fast feedback system. The −3 dB cutoff frequency of the correctors is about 70 Hz, which is the main limiting factor of the feedback performance. On the other hand, the phase delay induced by the eddy currents generated in the stainless steel vacuum chamber by the AC magnetic field is negligible, resulting in one degree at 60 Hz and two degrees at 100 Hz.

The LOF processing part is hosted in a VME-based Equipment Controller. The digital samples generated at 8 kHz rate by the Digital Receiver modules are passed through the VME bus to a PowerPC CPU board. A task running under the Linux operating system with the real-time extension RTAI[2], which provides the required deterministic response, executes the feedback algorithm. A multi-channel DAC converter board transforms the resulting digital output samples into analog signals that drive the corrector magnet power supplies. The system is connected to the accelerator control system by an Ethernet link. The operation of the feedback is remotely controlled from any Matlab session running on the control room UNIX workstations. In parallel to the feedback processing the PowerPC CPU board stores a large amount of beam position data at 8 kHz that can be uploaded in Matlab for data processing and visualization.

3.2 Operational Results

The basic feedback algorithm adopted is a PID (Proportional, Integral, Derivative) controller, whose transfer func-

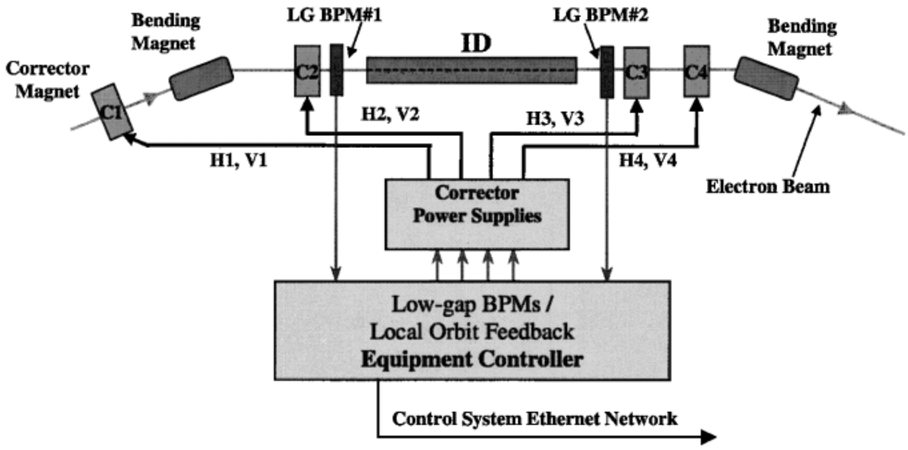

Figure 1. Layout of the local orbit feedback system.

tion in the z-plane is:

$$R(z)=K_P+\frac{K_I}{1-z^{-1}}+K_D(1-z^{-1})$$

An additional single-pole digital low pass filter limits the input signal dynamics to avoid non-linearities of the corrector magnet power supplies.

The LOF loop has been positively closed at a rate of 8 kHz in both vertical and horizontal planes. **Fig. 2** shows the vertical beam position spectra from 0 to 100 Hz measured by a low-gap BPM with LOF off/on. The following PID parameters have been used: $K_P=3$, $K_I=0.01$ and $K_D=10$. The low pass filter cut-off frequency has been set to 150 Hz.

While slow orbit drifts and lower frequency components of the beam noise spectrum are corrected by the PID controller, a different technique called 'harmonic suppression'[3] is used to effectively remove those specific components induced by the mains. The harmonic suppression scheme **(Fig. 3)** consists of a loop with a selective digital filter centered at the frequency to damp. The delay 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. The selective filter is a complex conjugate two pole digital resonator with two zeros in $z=\pm 1$. Its transfer function is:

$$H(z)=G\,\frac{(1-z^{-1})(1+z^{-1})}{1-(2r\cos\omega_0)z^{-1}+r^2z^{-2}}$$

where ω_0 is the resonance frequency, r is the amplitude of the two poles, which must be smaller than one for the stability condition and G is an overall gain factor. The width of the notch, which must be effective only at the selected frequency, can be changed by properly setting r.

As long as the notches are completely separated from each other, multiple harmonic suppressors centered at different frequencies can be implemented and run in parallel with a standard PID regulator **(Fig. 3)**. Moreover, as the beam noise components associated to 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

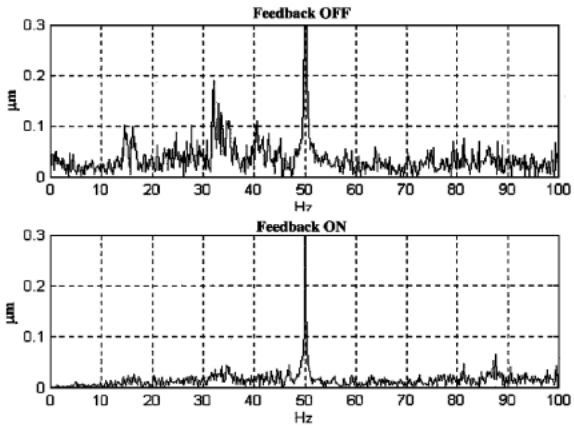

Figure 2. Vertical beam position spectra measured by a low-gap BPM with LOF off/on using the PID controller ($K_P=3$, $K_I=0.01$, $K_D=10$).

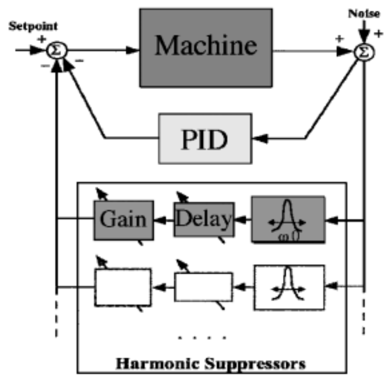

Figure 3. Block diagram of the LOF scheme showing the concurrent action of the PID controller and multiple harmonic suppressors.

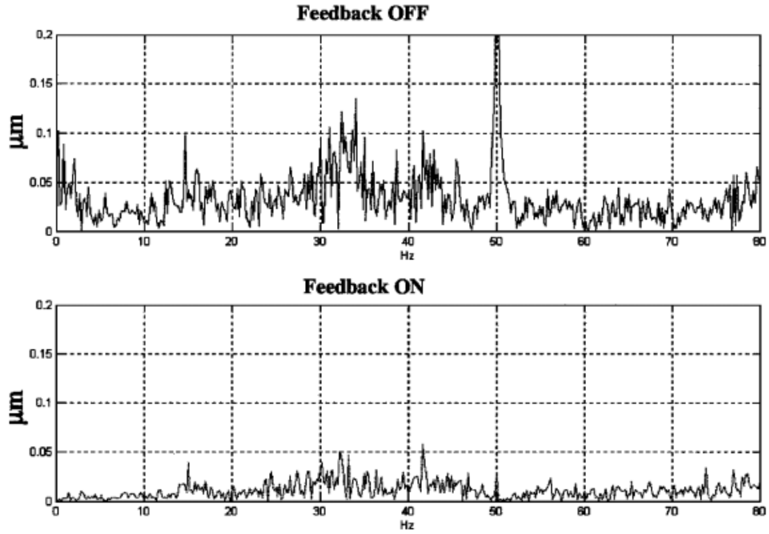

Figure 4.　Vertical beam position spectra measured by a low-gap BPM with LOF off/on using the PID controller ($K_P=3$, $K_I=0.01$, $K_D=10$) together with one harmonic suppressor centered at 50 Hz.

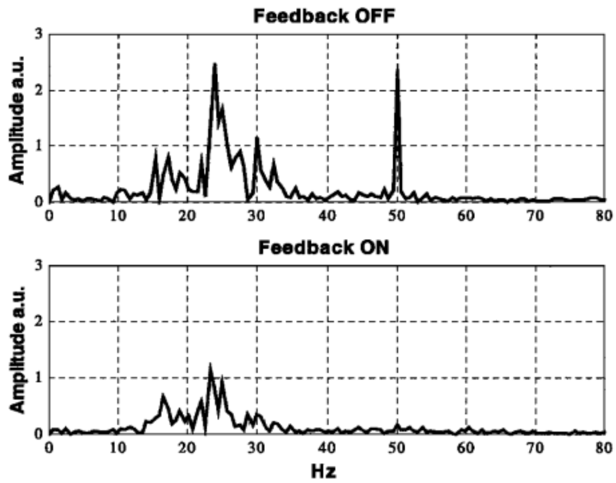

Figure 5.　Vertical photon beam position spectra with LOF off/on using the PID controller ($K_P=3$, $K_I=0.01$, $K_D=10$) together with one harmonic suppressor centered at 50 Hz.

rotation is large. The spectra in **Fig. 4** show the effect of the LOF with the combined action of the PID controller and one harmonic suppressor at 50 Hz. The rms of the vertical position signal in the 0–80 Hz range is reduced from 1.24 μm to 0.2 μm. The results have been verified by measuring the spectra of the photon beam position on a downstream photon BPM (**Fig. 5**).

4. The Electromagnetic Elliptical Wiggler Feed-Forward System

An Electromagnetic Elliptical Wiggler (EEW) has been in operation at ELETTRA since 1997 providing a source of circularly polarized radiation in the VUV/Soft X-ray region[4], with the helicity varied by modulating the horizontal magnetic field at frequencies up to 100 Hz. The EEW, which is installed in straight section 4, combines in one magnetic structure periodic horizontal and vertical fields. The electromagnets are powered by two Pulse Width Modulation power supplies featuring low ripple and good stability. The vertical field current is mono-polar (max 200 A) and generated in DC mode, while the horizontal one is bipolar (max ±300 A) and can be generated both in DC and AC mode. In designing the magnetic structure of the EEW special care was taken to minimize deleterious effects on the accelerator performance that arise from magnetic field errors. Residual first and second field integrals, resulting in closed-orbit distortion, are compensated by a feed-forward system based on external correction coils. Four fast power supplies (max ±5 A) featuring 1 kHz bandwidth drive two pairs of horizontal/vertical air-cored coils installed at each wiggler end.

In order to improve the dynamic correction of the field integral errors when the EEW is operated in AC mode a new scheme based on the high precision measurements provided by the two wideband low-gap BPMs has been recently developed.

4.1 System Overview

The layout of the EEW low-level control system is shown in **Fig. 6**. The Equipment Controller is a VME-based system hosting a CPU board that is in charge of the basic controls and is connected to the ELETTRA control system Ethernet network. ADC, DAC and digital I/O VME boards manage the I/O signals to control the two horizontal/vertical field power supplies and the four correction coil power supplies. The ADC and DAC boards provide 16-bit resolution and high stability (±10 ppm-full-scale/°C). A second CPU board equipped with one TMS320C40 Digital Signal Processor (DSP) is dedicated to the generation of the AC waveforms.

Two different operational modes are foreseen: DC and AC. In DC mode the settings of the EEW currents are carried out through slow ramps. A feed-forward loop runs during the ramps to compensate for the orbit distortion. The

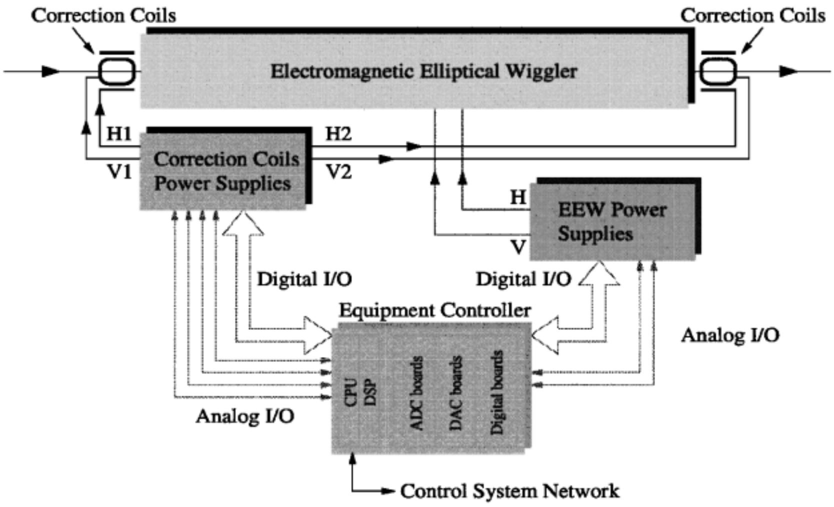

Figure 6. Layout of the EEW low-level control system.

correction values are calculated using a lookup table and continuously applied to the correction coil power supplies at 10 Hz data rate. The four values for each pair of horizontal/vertical wiggler settings contained in the lookup table are empirically determined by performing an off-line calibration based on the minimization of the closed-orbit distortion measured by the 'normal' ELETTRA BPMs. The tasks in charge of the generation of the ramps and the feed-forward loop run on the host CPU and drive the DAC boards through the VME bus.

In AC mode the control system acts as an arbitrary waveform generator with five independent channels driving the power supplies of the horizontal field and of the four correction coils; the vertical field current is kept constant. The digital samples corresponding to one period of the waveform for each of the five channels are downloaded into the DSP board via the VME bus. When the EEW is started the DSP board generates the desired waveforms by interpolating the downloaded samples and continuously applying the calculated values on the DAC boards at the rate of 10 kHz. Any waveform repetition frequency from 0.01 to 100 Hz can be chosen.

4.2 Optimized Feed-Forward Procedure for the AC Operational Mode

The orbit distortion produced by the EEW working in AC mode depends on the shape and on the repetition frequency of the waveform used to drive the horizontal field power supply. This is due to the limited bandwidth of the wiggler electromagnet and to non-linearities. As a consequence the lookup table used for the correction in DC mode cannot be employed in AC since it is determined by minimizing the orbit distortion in static conditions. Moreover, the 'normal' BPMs installed at ELETTRA do not provide the required precision and bandwidth to measure the orbit perturbations at the high EEW operating frequencies.

An iterative procedure employing the low-gap BPMs is currently used to optimize the corrections when operating in AC mode. It assumes that measuring and suppressing the orbit perturbation in two machine locations where the monitors are installed is sufficient to assure that the whole closed-orbit is corrected. The betatron phase advance between the two monitors is about 35° in the horizontal and 91° in the vertical plane.

Fig. 7 shows the setup used for the optimization of the correction system. As the time relationship between the horizontal field waveform and the orbit distortion produced is fundamental to find the optimal correction values corresponding to each point of the curve, a synchronized acquisition of the low-gap BPMs' data is necessary. The EEW horizontal power supply provides a zero-crossing signal made of 10 μs-long pulses generated on the positive-slope side of the current waveform. This signal is transmitted by means of a 4–20 mA current-loop link to the low-gap BPM Equipment Controller where it is first conditioned and then acquired by the PowerPC CPU board. A workbench based on Matlab has been developed to support the optimization procedure from the control room. A set of Matlab commands allows to operate the EEW and to process the data acquired from the low-gap BPM system.

The first step of the optimization procedure is the determination of the response matrix of the two pairs of horizontal/vertical correction coils with respect to the low-gap BPMs. The response matrix is empirically obtained by separately exciting each correction coil and measuring the corresponding horizontal/vertical orbit difference at the monitors; the resulting 4×4 matrix accounts also for possible cross talk between the two planes. The inverted response matrix is used to calculate the current in the coils to correct a given orbit error at the low-gap BPMs.

The second step is the measurement of the orbit distortion during one period of the horizontal current waveform while the EEW is running in AC mode. The zero-crossing pulses are used to precisely relate each point of the horizontal field waveform to the corresponding position errors at the low-gap BPMs. In order to filter out the background noise of the beam, which overlaps with the perturbation from the EEW,

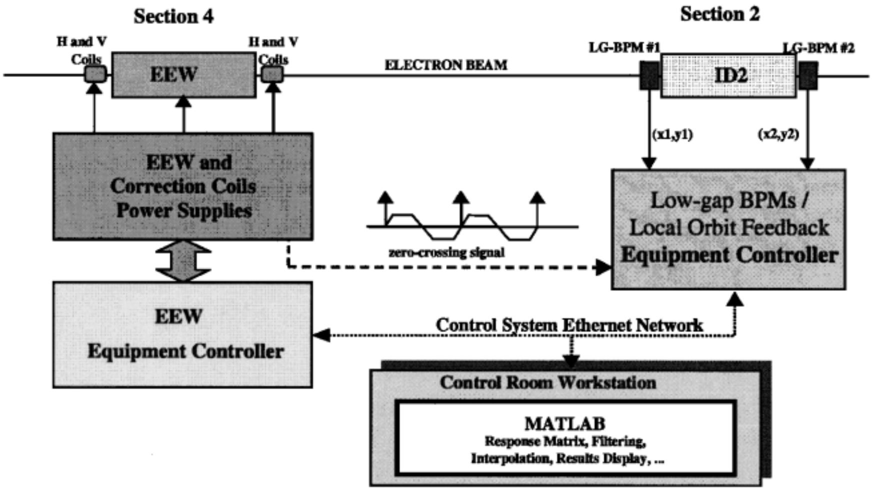

Figure 7. Setup for the optimization of the AC feed-forward correction.

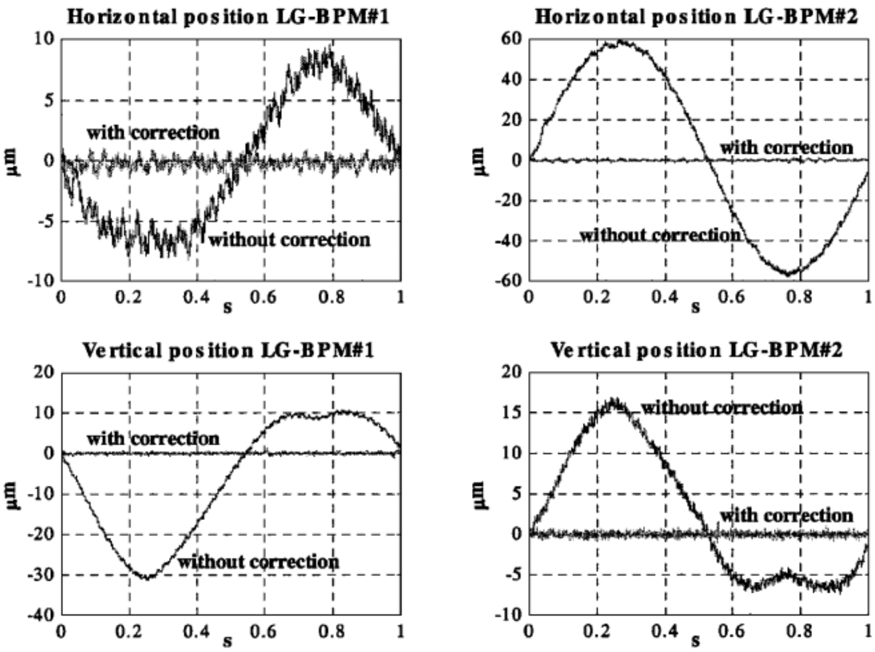

Figure 8. Orbit perturbation at the low-gap BPMs with feed-forward correction off/on when the EEW is operated with a sinusoidal waveform at 1 Hz.

the acquired positions are averaged over many periods by the PowerPC CPU. In this way non-periodical disturbances or periodical components at frequencies different from the EEW switching frequency and its harmonics are attenuated. The samples of one averaged period are passed to Matlab where unwanted components are further reduced by low-pass filtering and applying notch filters centered at 50 Hz and its harmonics. Interpolation is then performed in order to obtain four arrays of fixed length. The reference DC orbit value is eventually subtracted from each of them to get four data arrays representing the horizontal and vertical orbit errors measured at the two low-gap BPMs over one period. The correction curves to compensate for the measured orbit distortion are calculated by multiplying the four arrays above by the inverted response matrix. These new values are added to the pre-existing correction waveforms (zero at the first iteration) and downloaded into the EEW DSP board. This procedure is iterated until the residual error is minimized.

A Matlab script has been developed to carry out the above procedure that is normally executed automatically.

4.3 Operational Results

Fig. 8 illustrates an example of the achieved optimization. The EEW horizontal current is modulated between ±260 A using a sinusoidal waveform at 1 Hz, the vertical current is set to 160 A. The curves show the averaged horizontal/vertical orbit perturbation at the low-gap BPMs without feed-forward correction and after four iterations of the optimization

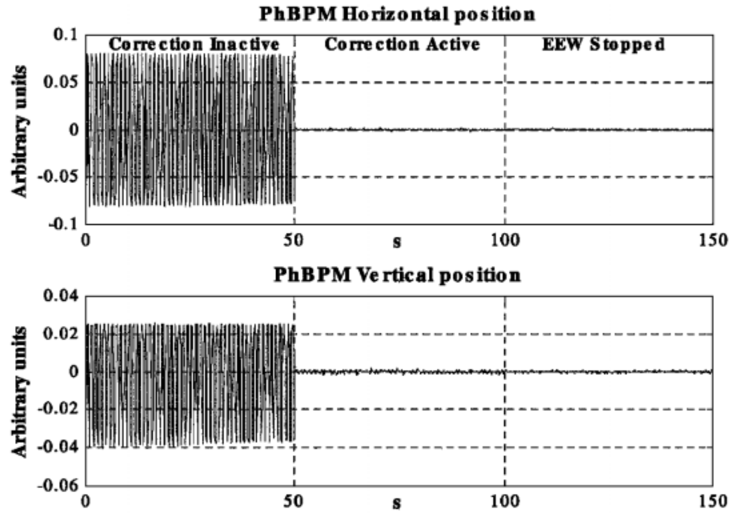

Figure 9.　Photon BPM's horizontal and vertical readings showing the action of the feed-forward correction system when the EEW is modulated with a sine-wave at 1 Hz and, for comparison, with EEW stopped.

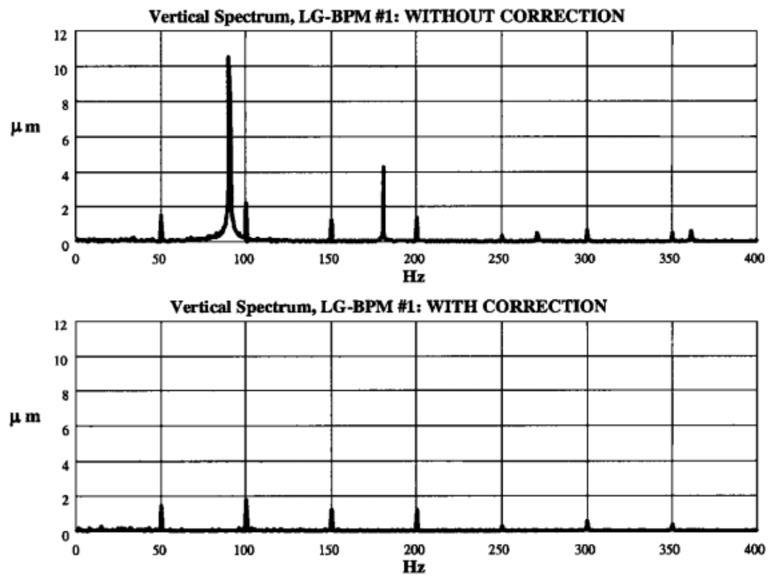

Figure 10　Vertical beam position spectra measured by a low-gap BPM showing that the harmonics of the EEW switching frequency (sine waveform at 90 Hz) are eliminated by the feed-forward correction system.

procedure, with the perturbation reduced to a negligible level. In order to verify these results in another location of the ring the position of the photon beam generated by the undulator in section 6 has been measured using a photon BPM. The plots in **Fig. 9** are the horizontal and vertical positions measured in three different cases: feed-forward correction system inactive, active and EEW stopped.

The feed-forward correction system has been optimized for several AC waveforms. For each combination of waveform, frequency and vertical current a dedicated optimization is executed to find the respective correction coil arrays. Trapezoidal waveforms at 0.1 Hz with one-second ramps between flat-tops and sinusoidal waveforms running at 0.1 and 11 Hz are examples of AC operational modes presently requested by the beam line users.

Analysis of the residual orbit distortion can be made also in the frequency domain where the orbit noise components due to the EEW can be easily distinguished from the background noise of the beam. **Fig. 10** shows the spectra of the vertical position measured by one low-gap BPM without/with correction. In this case the EEW is operating with a sinusoidal waveform at 90 Hz. The noise components due to the modulation of the horizontal current (±260 A) are represented by the spectral lines at 90 Hz and its multiples. The lower plot clearly shows that no residual perturbation due to the EEW is present on the beam when the feed-forward correction system is working. Similar spectra can be also measured using the photon BPMs.

5. Conclusions

By combining sub-micron resolution and high readout rate the new low-gap BPMs open the way to the implementation of fast orbit feedback and feed-forward systems that improve the beam stability at ELETTRA.

The first of a series of fast local orbit feedback systems has been installed. It takes advantage of the concurrent action of a PID controller and harmonic suppressors to respectively correct lower frequency and mains-induced components of the beam noise.

A procedure to optimize the feed-forward correction system of the EEW operated in AC mode has been developed and successfully implemented. The optimized system effectively compensates the closed-orbit distortions allowing the EEW to produce circularly polarized radiation with modulated helicity at frequencies up to 100 Hz without disturbing the operation of the other beam lines.

6. Acknowledgements

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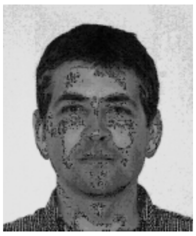

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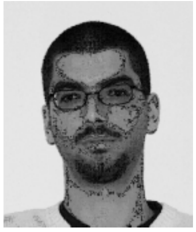

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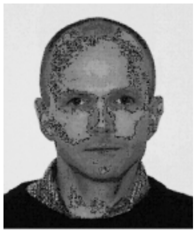

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