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A METHOD OF LOCAL IMPEDANCE MEASUREMENT BY SINE-WAVE BEAM EXCITATION *

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Abstract

We have developed and tested a technique, which significantly improves the accuracy of the orbit bump method of local impedance measurement. This technique is based on in-phase sine-wave (AC) excitation of four fast correctors adjacent to the vacuum chamber section, impedance of which is measured. The narrow-band sine-wave signals provide better signal-to-noise ratio. Use of fast correctors to the beam excitation eliminates the systematic error caused by hysteresis. The systematic error caused by orbit drift is also suppressed because the measured signal is not affected by the orbit motion outside the excitation frequency range. The measurement technique is described and the result of experimental testing carried out at NSLS-II is presented.

INTRODUCTION

The beam intensity in storage rings is limited by collective effects of beam dynamics resulting from the interaction of a particle beam with electromagnetic fields induced in a vacuum chamber by the beam itself. This interaction can result in serious troubles affecting accelerator performance such as overheating of vacuum chamber components or instability of the beam motion.

The beam-impedance interaction manifests itself in several effects, which can be measured quite precisely using modern beam diagnostic instruments and measurement techniques. So the impedance can be measured experimentally using beam- based techniques. For the longitudinal broadband impedance, the measurable effects are current-dependent bunch lengthening, synchronous phase shift, and energy spread growth due to microwave instability. For the transverse broadband impedance, the measurable effects are current-dependent shift of betatron tunes and rising/damping time of chromatic head-tail interaction.

The impedance distribution along the ring is not uniform and beam-based measurement of local impedance is a subject of importance for accelerator physicists. For example, low-gap light-generating insertion devices make significant contributions to the total impedance of a light sources. Thus, measurement of impedances of already installed insertion devices is helpful to predict the impedance evolution of light sources while installing new insertion devices.

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ORBIT BUMP METHOD

The interaction of a bunched beam with the transverse broadband impedance is characterized by the kick factor:

$$k_\perp = \frac{1}{2\pi}\int_{-\infty}^{\infty} Z_\perp(\omega)\, h(\omega)\mathrm{d}\omega\,, \tag{1}$$

where $Z_\perp(\omega)$ is the frequency-dependent transverse impedance; $h(\omega) = \tilde{\lambda}(\omega)\tilde{\lambda}^*(\omega)$ is the bunch power spectrum; $\tilde{\lambda}(\omega) = \int_{-\infty}^{\infty} \lambda(t)e^{-i\omega t}\mathrm{d}t$ is the Fourier transform of the bunch longitudinal density $\lambda(t)$ normalized as $\int_{-\infty}^{\infty} \lambda(t)\mathrm{d}t = 1$. A transverse dipole kick $\Delta x'$ caused by the beam-impedance interaction is

$$\Delta x' = \frac{q}{E/e}k_\perp x\,, \tag{2}$$

where $q = Ne$ is the beam charge, N is the number of particles, x is the beam transverse offset, E is the beam energy, e is the electron charge.

A local transverse impedance acts on the beam as a defocusing quadrupole, strength of which depends on the beam intensity. The orbit bump method [1, 2] is based on the measurement of a wave-like orbit distortion created by the wakefield kick $\Delta x'$ (2) proportional to the beam charge and its transverse position at the impedance location. If a local orbit bump is created at the impedance location, the intensity-dependent orbit distortion is:

$$\Delta x(s) = \frac{\Delta q}{E/e}k_\perp x_0 \frac{\sqrt{\beta(s)\beta(s_0)}}{2\sin\pi\nu_\beta}\cos\left(|\mu(s)-\mu(s_0)| - \pi\nu_\beta\right)\,, \tag{3}$$

where x_0 is the orbit bump height, s_0 is the impedance location, Δq is the bunch charge variation, ν_β is the betatron tune, β is the beta function, and μ is the betatron phase advance. This wave-like orbit distortion can be measured using beam position monitors, and the wave amplitude is proportional to the kick factor at the bump location. To reduce the systematic error caused by intensity-dependent behavior of the BPM electronics, this error is also measured and then subtracted.

The orbit bump method is more sensitive than the method [3] based on the measurement of intensity-dependent betatron phase advance along the ring because the beam position monitors (BPMs) are used in the narrowband orbit mode rather than in the broadband turn-by-turn mode, and the noise is much smaller.

Evolution of BPM electronics resulted in great improvement of the bump method accuracy from 20 – 40 μm at the very beginning of the method development [4] to

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0.2 – 0.5 μm) in the resent measurements [5]. Two examples of the measured intensity-dependent orbit distortions with the fitting functions (3) are shown in Fig. 1 (VEPP-4M, 1998) and Fig. 2 (Diamond Light Source, 2014).

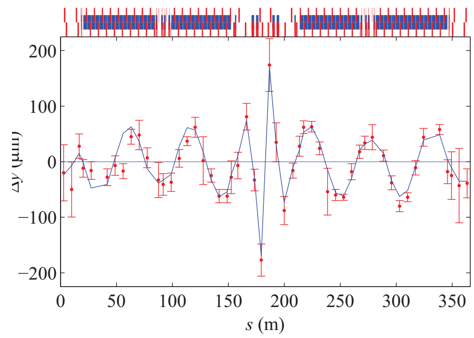

Figure 1: Intensity-dependent orbit distortion (VEPP-4M collider, 1998).

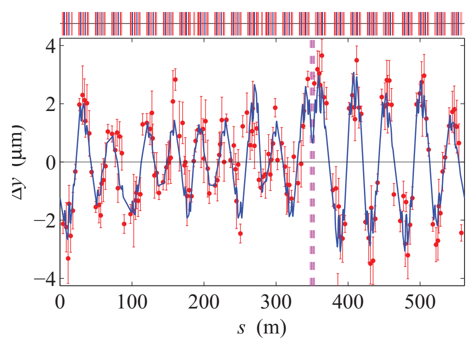

Figure 2: Intensity-dependent orbit distortion (Diamond Light Source, 2014).

Further improvement looks problematic because of the systematic errors caused by hysteresis effects of correctors and by the orbit drifts along the measurement.

AC BUMP TECHNIQUE

To improve the bump method accuracy, we propose a technique based on excitation of an AC orbit bump by use of fast orbit correctors [6]. The fast correctors are working in a bandwidth up to hundreds Hertz and they are typically installed at synchrotron light sources for fast orbit feedbacks. Recent developments of lattice correction techniques using an orbit response matrix measured by sine-wave excitation of the fast correctors show that the AC orbit can be measured with a precision of the order of 0.02 μm [7, 8].

The proposed technique has been tested at NSLS-II by measuring the vertical kick factor of a variable-gap in-vacuum undulator. Four fast correctors located nearby the undulator are selected as shown in Figure 3. The undulator is located in the center of the straight section, the fast correctors are marked as FC, the beam position monitors are marked as BPM, the beta functions are also shown.

To create the AC orbit bump, these four correctors are excited simultaneously by a sine-wave driving signal. Proper excitation amplitudes for the correctors are obtained by scaling the driving signal with the factors pre-calculated using

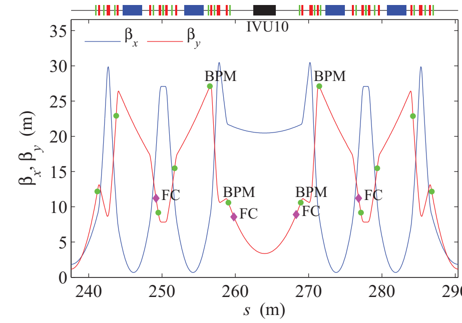

Figure 3: Beta functions and positions of BPMs and fast correctors in the NSLS-II Cell 10. The undulator is located in the center of the section.

the model lattice. The same driving signal is used as a reference for synchronous detection of the beam oscillations measured by BPMs. Figure 4 shows an example of single-BPM data together with the reference signal.

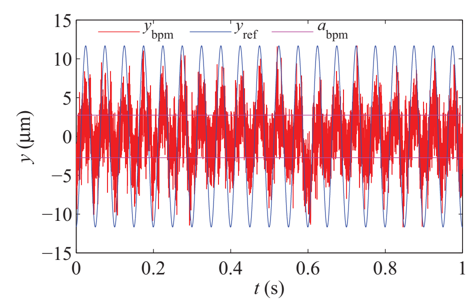

Figure 4: Beam oscillations measured by a BPM and the reference signal.

If the bump is perfectly matched, the beam oscillates between the outer two correctors and the orbit outside the bump is not perturbed. In reality, a residual orbit perturbation outside the bump is caused by the lattice model imperfections. An example of the measured AC orbit bump in comparison with the ideal (simulated) one is shown in Figure 5. The orbit perturbation outside the bump is a source of a systematic error, but it does not exceed 5% for this example.

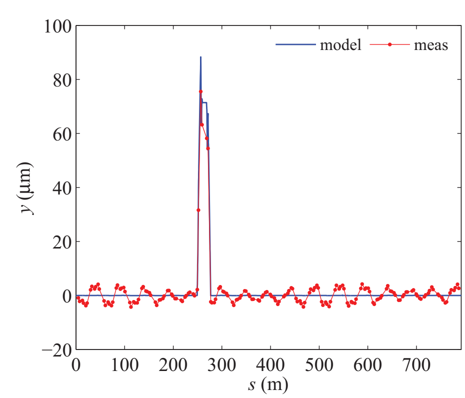

Figure 5: Measured (red) and simulated (blue) AC orbit bumps.

To measure the kick factor of a vacuum chamber section, the AC bump is created in that section and the orbit oscillation is measured by all BPMs as a function of the beam

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charge variation Δq. The intensity-dependent orbit distortion Δx at the location of each BPM is a difference of the oscillation amplitudes measured by the BPM at different beam charge.

EXPERIMENTAL RESULTS

To test the AC bump technique, the vertical kick factor of a variable-gap in-vacuum undulator has been measured in two cases: closed gap of 6 mm (maximal impedance) and open gap of 25 mm (minimal impedance).

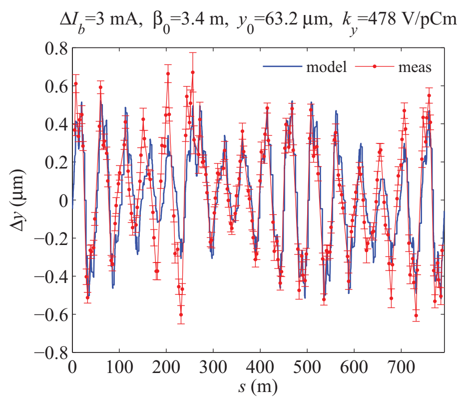

Figure 6: Measured (red dots) and model (blue line) AC orbit distortion. The undulator gap is 6 mm.

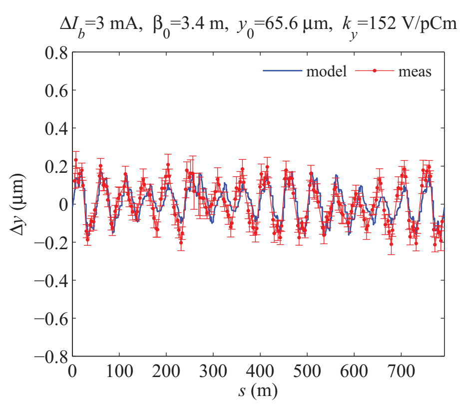

Figure 7: Measured (red dots) and model (blue line) AC orbit distortion. The undulator gap is 25 mm.

The fast correctors were excited by a sine-wave drive signal with the frequency of 20 Hz. The maximal kick angle of the NSLS-II fast corrector is limited by its power supply and can not exceed 15 μrad. The beam oscillation is measured simultaneously by 180 button-type BPMs with the sampling frequency of 10 kHz [9]. The measured noise power spectral density of NSLS-II BPMs is about 0.03 $\mu\text{m}/\sqrt{\text{Hz}}$. The BPM data were measured during $T = 10$ s, therefore the bandwidth is $\delta f = 1/T = 0.1$ Hz [8] and the noise-limited resolution is about 0.01 μm.

The AC orbit was measured at two values of the beam current: 2 mA and 5 mA (the beam charge was 5.3 nC and 13.2 nC, respectively). The measured AC orbit distortions (3) are shown in Figure 6 and Figure 7. The error bars represent r.m.s. deviation of 10 measurements. As one can see, the measurement resolution is good enough to measure the orbit distortion of the order of 0.1 μm. The kick factor k_y is obtained by fitting the model orbit distortion (3) with the measured data using k_y as a fit parameter.

CONCLUSION

For local impedance measurement, a fast and precise technique based on excitation of an AC orbit bump using fast orbit correctors has been developed and tested at NSLS-II. The results have demonstrated that the measurement resolution is good enough to measure the orbit distortion of the order of 0.1 μm, which is an order of magnitude smaller than the sensitivity of the conventional bump method.

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