MEASUREMENT OF BEAM PARAMETERS IN THE VEPP-5 DAMPING RING USING BETATRON OSCILLATIONS DECOHERENCE*

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Abstract

The measurement of beam parameters during the commissioning of VEPP-5 Damping Ring is presented. Coherent betatron oscillations of the 380-MeV electron beam were induced by a fast kick. Electrostatic beam position monitors were used to obtain the turn-by-turn transverse beam position data. The form and behavior of the envelope of oscillations are determined by the beam parameters, chromaticity and nonlinear detuning. The values of beam emittance $\epsilon = 1.5 \cdot 10^{-8}$ m·rad, energy spread $\delta = 3.6 \cdot 10^{-4}$ and beam length $\sigma_l = 1.5$ cm have been obtained from the analysis of the beam envelope, nonlinear detuning and chromaticity measurements. The results are in a good agreement with theoretical predictions which were made for calibrated model of the Damping Ring.

INTRODUCTION

VEPP-5 Injection Complex is designed for the production of intense high-quality electron and positron beams [1]. Damping Ring stores the electron and positron beams of 510 MeV which are injected from the Linac. These beams are to be used at the electron-positron colliders at BINP and plasma wake field acceleration (PWFA) facility [2]. The necessary requirements to the produced beams are of $2 \cdot 10^{10}$ particles in the bunch, emittance of ($\epsilon_x = 2 \cdot 10^{-8}$ m·rad, $\epsilon_y = 0.5 \cdot 10^{-8}$ m·rad with the rate of the beam accumulation 10^{10} positrons per second.

At the present moment Injection Complex and its Damping ring are under commissioning. Currently the electron beam with energy 380 MeV has been stored in the Damping Ring; the experiments with positron beam injection and storage are planned for October 2012.

There are 17 electrostatic beam position monitors (BPMs) in the Damping Ring. Each monitor can record the transverse coordinates of beam centroid over 32000 turns or less. Turn-by-turn measurements from BPMs can be used for the storage ring optics measurements as well as indirect beam parameters measurements. The envelope of coherent betatron oscillations is influenced by the energy spread, transverse and longitudinal beam sizes and emittances. Therefore, the analysis of oscillation envelopes [3] or synchrotron spectra [4] can yield these beam parameters.

This simple technique was used during the Damping Ring commissioning with electron beams and will be used for positron beams.

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BETATRON OSCILLATION ENVELOPE

Transverse betatron beam oscillations induced by fast inflector kick. For low enough beam intensity betatron particle motion is independent for the all particles in the beam. Single particle turn-by-turn transverse position may be written as

$$x(t) = \sqrt{2I\beta}\cos(2\pi\int_0^t \nu(t)dt + \psi_0), \qquad (1)$$

where β – beta-function at the point of BPM location, ψ, I – action-angle coordinates [3].

Initially kicked beam behaves like a single particle (coherent oscillations) but because of betatron tune spread the decoherence is developed in several thousands of turns and the beam centroid oscillations amplitude decreases due to detuning of betatron oscillations.

There are two main sources of tune spread: chromaticity and amplitude-dependent tuneshift

$$\nu = \nu_0 + \delta\xi + aI, \qquad (2)$$

where $\delta = \Delta p/p_0$, ξ – chromaticity, a is the constant describing amplitude-dependent tuneshift. Assuming that the initial beam distribution is Gaussian in longitudinal and transverse planes one can express the position of beam centroid as:

$$< x(t) >= \sqrt{2\beta I(t)}\cos(\psi(t) + \psi_0) \qquad (3)$$

where

$$I(t) = \frac{1}{1+\theta^2}\exp\left(-\frac{Z^2}{2}\cdot\frac{\theta^2}{1+\theta^2}\right)\cdot \cdot\exp\left(-2\left(\frac{\xi\delta}{\nu_s}\right)^2\sin^2(\pi\nu_s t)\right) \qquad (4)$$

$$\psi(t) = 2\pi\nu_0 t + \frac{Z^2}{2}\cdot\frac{\theta}{1+\theta^2} + 2\arctan\theta.$$

Here $Z = \sqrt{2I_{max}/\epsilon}$ – kick strength, $\theta = 2\pi a\epsilon t$, ν_s - synchrotron frequency. One can see that the form of the oscillation envelope depends on two values $\xi\delta$ and $a\epsilon$. Amplitude-tune dependence contributes as the main damping of the oscillations amplitude; chromaticity modulates the envelope with synchrotron frequency. Given the values of ξ and a from preliminary measurements, one can deduce energy spread and beam emittance by fitting the formula (Eq. 4) to the envelope by varying ϵ and δ.

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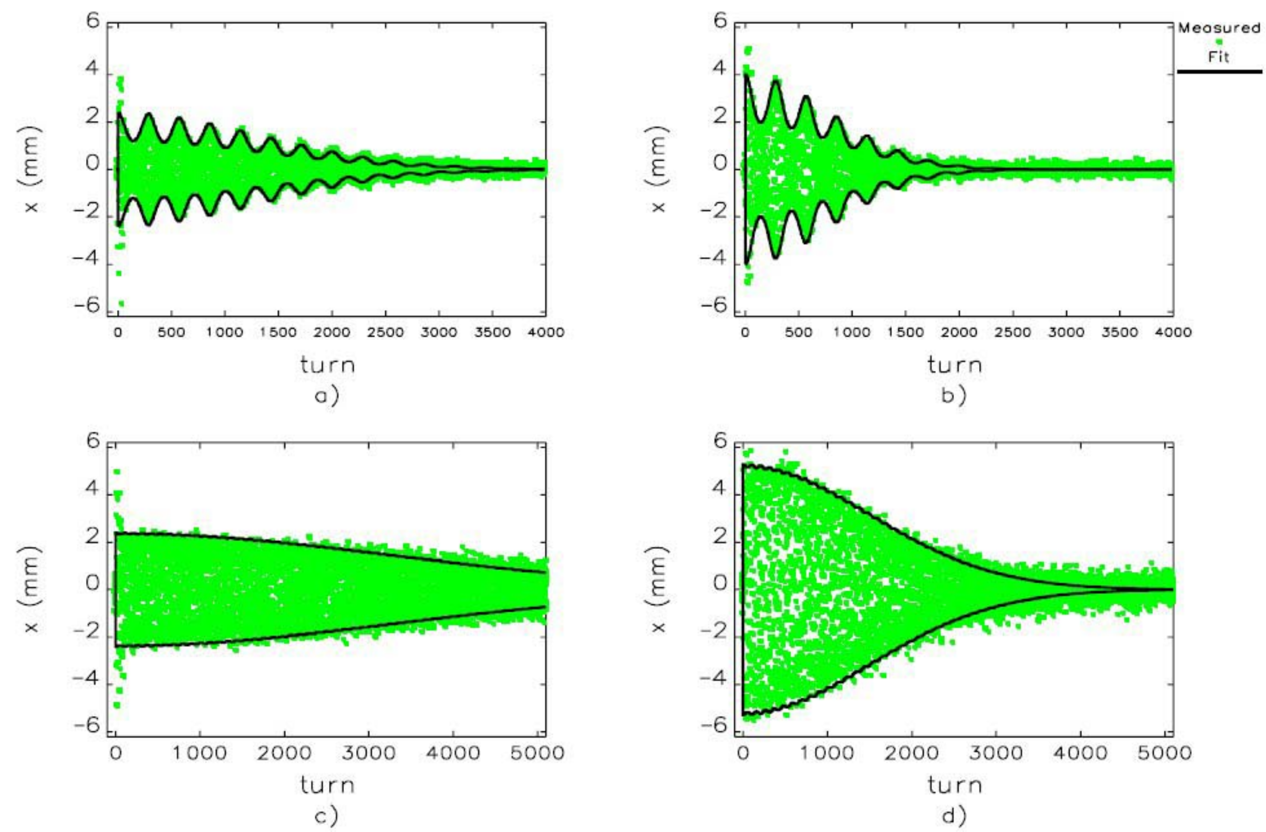

Figure 1: Horizontal betatron oscillations after the kick (green dots) and envelope fit (black solid line) calculated from Eq. 4. At the two upper plots (a,b) the turn-by-turn measurements were performed for the machine with natural chromaticity ($xi = -6.0$). At the bottom plot the chromaticity is compensated with sextupoles.

Beam length is deduced from energy spread and synchrotron frequency

$$\sigma_l = \frac{\alpha_p c}{2\pi f_0 \nu_s}\delta$$

where α_p - momentum compaction factor, L - machine circumference, f_0 - revolution frequency.

The technique is valid for low-current beams when the beam - vacuum chamber interactions can be neglected.

BEAM TILT DUE TO CHROMATICITY

It is interesting to note that chromatic decoherence results in beam tilt developed in the plane of oscillations. Beam synchrotron oscillations can be presented in the form

$$\delta = \delta_0 \cos(2\pi\nu_s t + \psi_s), \tag{5}$$

where δ and ψ_s – amplitude and phase of oscillations. Then longitudinal position of particle may be written as

$$s(t) = s_0 \sin(2\pi\nu_s t + \psi_s)$$

where $s_0 = \delta_0 L\alpha_p/(2\pi\nu_s)$.

Adding Eq. 5 to (1) and (2) one obtains

$$x(t) = \sqrt{2I\beta}\cos(\psi_0 + \\ + 2\pi\int_0^t (\nu_0 + aI + \xi\delta_0\cos(2\pi\nu_s t + \psi_s))dt) \tag{6}$$

After the half of synchrotron oscillation period ($t_0 = 1/(2\nu_s)$) the particle position is

$$x = \sqrt{2I\beta}\cos\left(\psi_0 + \frac{\pi(\nu_0 + aI)}{\nu_s} - \frac{2\xi\delta_0}{\nu_s}\sin\psi_s\right)$$

Since the longitudinal particle position at the same time is $s(t_0 = 1/(2\nu_s) = -s_0\sin(\psi_0)$ there is a correlation between transverse and longitudinal position of particle in the beam:

$$x = \sqrt{2I\beta}\cos\left(\psi_0 + \frac{\pi(\nu_0 + aI)}{\nu_s} + \frac{4\pi\xi}{L\alpha_s}s\right) \tag{7}$$

This correlation is preserved for the several turns around t_0 because the synchrotron oscillations are slow. Betatron oscillations are much faster so one can choose a turn with s-independent phase addition equal to $\pi/2 + \pi n$. Then

$$x \sim \sqrt{2I\beta}\sin\left(\frac{4\pi\xi}{L\alpha_p}s\right) \tag{8}$$

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For the Damping Ring ($L = 27$ m, $\xi = 6.0, \alpha_p = 0.028$, $s \sim 1$ cm) one can replace the sine function with its linear approximation:

$$x \sim \sqrt{2I\beta}\frac{4\pi\xi}{L\alpha_p}s \quad (9)$$

Therefore, the beam tilt depends only on kick amplitude and chromaticity.

The effect of beam tilt is described in details in [5] where it was used to generate very short x-ray pulses. Beam tilt can also be used to modulate the beam in the Damping Ring with a collimator for the plasma wake-field acceleration experiment.

EXPERIMENT IN DAMPING RING AND RESULTS

The results of two series of measurements and beam envelope fits are displayed at the Fig. 1. The first pair of data sets (1a, 1b) was recorded with the natural chromaticity in the Damping Ring $\xi = -6.0$ and different kick strengths. At the other data sets (1c, 1d) chromaticity was corrected with sextupoles. In the Fig. 1a, 1b the form of envelope chromatic modulation allows us to find the energy spread. In the Fig. 1c, 1d the beam emittance can be found from the decoherence envelope. Combined fitting of two data series with different kick strengths and chromaticity gives energy spread $\delta = 3.6 \cdot 10^{-4}$ and emittance $\epsilon = 1.5 \cdot 10^{-8}$ m·rad (with 5% accuracy).

The equilibrium length of the beam with measured energy spread is $0.4 - 1.5$ cm.

This result is in a the good agreement with the design prediction of equilibrium beam parameters for low-intensity beams. For the design beam with $2 \cdot 10^{10}$ particles, the parameters δ and ϵ will have a factor of 2 bigger values due to beam heating by the intrabeam scattering.

CONCLUSION

The theory of betatron oscillations decoherence was applied to the VEPP-5 Damping Ring electron beam. For the beam with energy 380 MeV the measured energy spread is $3.6 \cdot 10^{-4}$, emittance is $1.5 \cdot 10^{-8}$ m·rad and bunch length 1.5 cm which is close to the design parameters.

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REFERENCES

[1] V. Anashin et al. "Damping Ring for Injection Complex VEPP-5" preprint. Budker Institute of Nuclear Physics. Novosibirsk, 1995.

[2] Petrenko A.V. et al. "The Facility of 500 MeV Plasma Wake-Field Acceleration Experiments at Budker INP". Proceedings of Advanced Accelerator Concepts 2010, Annapolis, MD, USA (2010), p. 467-471

[3] R.E. Meller, A.W. Chao et al. "Decoherence of Kicked Beams". SSC-N-360. 1987.

[4] T. Nakamura, K. Soutome et al. "Chromaticity for energy spread measurement and for cure of transverse multi-bunch instability in the SPRING-8 Storage Ring". PAC'01, proceedings.

[5] W. Guo et al. "Generating picosecond x-ray pulses in synchrotron light sources using dipole kickers". Phys. Rev. ST Accel. Beams 10, 020701 (2007).

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