

MEASUREMENTS OF THE RADIATION DAMPING TIME VIA OPTICAL METHODS*

V. E. Maior^{1,2,†}, M. V. Timoshenko, V. L. Dorokhov^{2,3}, O. I. Meshkov¹,

Budker Institute of Nuclear Physics, Novosibirsk, Russia

¹also at Novosibirsk State University, Novosibirsk, Russia

²also at SRF SKIF, Boreskov Institute of Catalysis, Koltsovo, Russia

³also at Novosibirsk State Technical University, Novosibirsk, Russia

Abstract

The radiation damping time is a crucial parameter that depends on the overall magnetic structure of the accelerator. Accurate measurement of this characteristics of installation can provide insights into the fidelity of the accelerator model by allowing for a comparison with calculated damping time values. In this study, we present a series of measurements of radiation damping times at the VEPP-4M and VEPP-2000 collider at BINP. In order to determine the damping time, we acquired the transverse beam profile using a digital camera. The results include study of the damping times at revolution frequencies and different energies of the beams.

INTRODUCTION

Radiation damping is a natural physical phenomenon in electron storage rings, arising from synchrotron radiation energy loss and subsequent energy recovery by radio frequency (RF) cavities. This mechanism leads to an exponential decrease in the amplitude of particle oscillations, with a radiation damping time. This parameter directly depends on the structure of the accelerator's magnetic lattice, including bending magnets, quadrupoles, and insertion devices. Accurate measurement of the radiation damping time is important for realistic modeling of beam dynamics and for verification of the theoretical accelerator model.

The comparison between model data and experimentally measured damping times is highly valuable. It provides information about the behaviour of a real installation, which may differ from an idealized model due to imperfections in the magnetic system, alignment errors, or unmodeled non-linear effects. Attenuation time measurements can be useful for modern colliders and low-emittance synchrotron radiation sources, where an accurate understanding of the accelerator structure and system behaviour is important.

The times of radiation damping of vertical, horizontal, and longitudinal beam oscillations are determined through the damping decrements, which are interrelated via Robinson's theorem [1-3]:

$$\alpha_x + \alpha_e = 3\alpha_y$$

$$\alpha_x = \frac{U_0}{2E_0T_0}(1-D), \quad \alpha_e = \frac{U_0}{2E_0T_0}(2+D), \quad \alpha_y = \frac{U_0}{2E_0T_0},$$

where E_0 is the energy of an electron circulating on the equilibrium orbit; U_0 represents the total energy loss per

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† v.boiyarkina@g.nsu.ru

revolution; T_0 is the orbital period of the electron on the equilibrium orbit; and D is a dimensionless parameter characterizing the geometric and focusing properties of the accelerator's magnetic system:

$$D = \frac{\oint c\mathcal{D}/\rho(1/\rho^2-2k) ds}{\oint 1/\rho^2 ds} = \frac{\oint c\mathcal{D}(1-2n)/\rho^3 ds}{\oint 1/\rho^2 ds},$$

where \mathcal{D} is the dispersion function; $n = kp^2$ is the field index (measuring the magnetic field fall-off); and k is a parameter describing the focusing strength of the magnets.

In this paper, we present a series of radiation damping time measurements conducted at the electron-positron synchrotron VEPP-3 (a booster for the VEPP-4M collider [4]) and VEPP-2000 collider [5]. The transverse beam profile was recorded using optical methods, namely a digital camera, which is particularly attractive due to its sufficient temporal resolution, cheapness and ease of use, making it a convenient tool for routine diagnostics. Measurements were carried out at various beam energies and rotation frequencies, allowing us to observed the dependence of damping time on accelerator parameters. The obtained experimental results are compared with simulations to assess the accuracy of the current lattice model.

DESCRIPTION OF EXPERIMENTAL INSTALLATIONS

The measurements were carried out on a VEPP-3 synchrotron (some parameters are listed in Table 1) [6] at beam energies of 428, 500, and 600 MeV. At the VEPP-2000 collider (Table 1), measurements were performed only at 405 MeV.

Table 1: Main Parameters of VEPP-3, VEPP-2000

| | VEPP-3 | VEPP-2000 |
|----------------------|-------------------------------------|--|
| Circumference | 74.39 m | 24.39 m |
| Revolution frequency | 4030.0 kHz | 12292.5 kHz |
| Energy | 450-2000 MeV | 160-1000 MeV |
| Horizontal emittance | 9-292 $\mu\text{m}\cdot\text{mrad}$ | 0.14 $\mu\text{m}\cdot\text{rad}$ (for 1 GeV energy) |

The beam was excited by a kick from an electromagnetic kicker, inducing beam oscillations and increasing its transverse size. Images were acquired by capturing synchrotron radiation from a bending magnet using a CMOS digital camera MER-131-75 GM [7]. The exposure time and data

acquisition rate were fixed during the damping process measurements, with the camera trigger synchronized to the beam kick.

In all cases, observations were made with a single bunch at a beam current of 1.0–0.1 mA. The exposure time varied between 10–150 μs . For measurements on VEPP-3 the data acquisition rates were: 220 Hz at 428 and 500 MeV, and 400 Hz at 600 MeV. When measuring on the ring of the VEPP-2000 collider, the frame rate of the camera was 1.1 kHz. To increase the frame rate, we set the ROI of the image and the mixing coordinates of the area so that the beam image fell into the center of the ROI.

The recorded images were approximated using a two-dimensional Gaussian distribution, accounting for rotation. The fitting results provided the beam size $\sigma_{x,y}$, incorporating the rotation of the image, i.e., without projecting the size onto the vertical or radial axes of the camera matrix.

The regression analysis of the dependence of the observed beam sizes $\sigma_{x,y}$ on time was performed using the following expression:

$$\sigma_{x,y}^2 = a \exp(-2\lambda t) + \sigma_{x_0,y_0}^2,$$

where σ_{x_0,y_0} represents the apparent equilibrium beam size, t is the recording time, and λ is the damping decrement in units of $[\text{s}^{-1}]$.

EXPERIMENTAL RESULTS

VEPP-3

Figure 1 shows the beam images at the beginning of the damping process observation and after the beam returns to its equilibrium size.

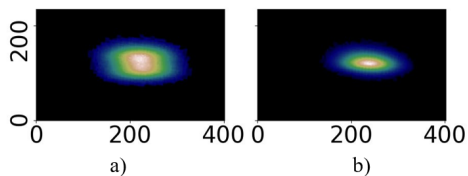


Figure 1: Examples of experimentally obtained beam images at an energy of 428.6 MeV, where (a) the beam after the deflector impact, (b) the beam after observing the attenuation.

Figure 2 displays the transverse profiles of the images presented in Fig. 2, where it is evident that the beam sizes changed noticeably after excitation by a kicker.

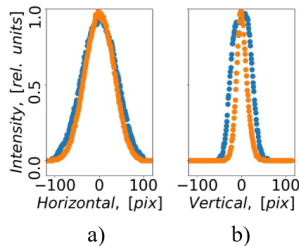


Figure 2: Typical recorded transverse beam profiles, where (a) horizontal, (b) vertical.

Figure 3 presents the curves of transverse size variations for two damping times obtained at different revolution frequencies at a beam energy of 428 MeV. It can be seen that vertical damping was slightly faster than horizontal damping, which is explained by differences in the mechanisms of radiative damping.

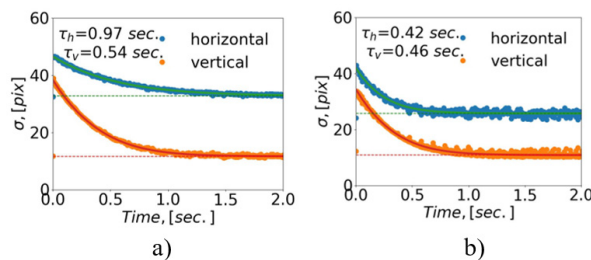


Figure 3: The dependences of the beam size change. Energy 428.6 MeV, exposure time ≈ 120 microseconds, registration frequency 220 Hz. For reference frequencies: (a) 4028.82 kHz; (b) 4030.62 kHz.

Figure 4 shows the experimental damping decrement values for three operational modes at different beam energies in the storage ring. A monotonic increase in the damping decrement (i.e., a decrease in damping time) with rising revolution frequency is observed. As the energy increases, the damping time decreases, which corresponds to the growth of synchrotron radiation power ($\sim E^4$).

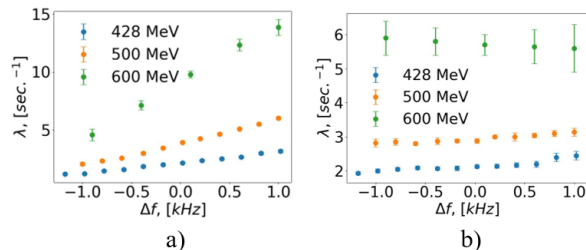


Figure 4: The dependences of the decrement on the frequency of circulation are: (a) horizontal; (b) vertical.

VEPP-2000

An experiment to measure the damping time of radial betatron oscillations at a beam energy of 405 MeV was conducted at the VEPP-2000 collider.

A typical image of the beam oscillations is shown in Fig. 5.

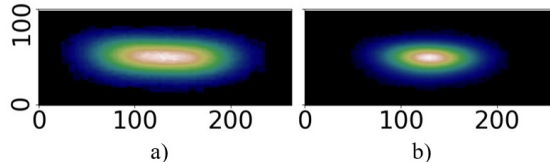


Figure 5: Examples of experimentally obtained beam images at an energy of 405 MeV, where (a) the beam after the deflector impact, (b) the beam after observing the attenuation.

Figure 6 displays the transverse profiles of the images presented in Fig. 5, where it is evident that the beam sizes changed noticeably after excitation by a kicker.

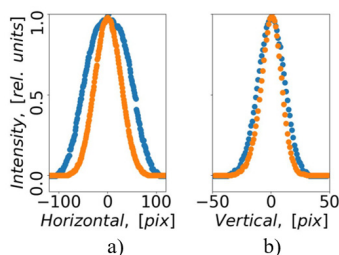


Figure 6: Typical recorded transverse beam profiles, where (a) horizontal, (b) vertical.

Figure 7 shows the curves of change in transverse dimensions for two attenuation periods obtained at different rotation frequencies. It can be seen that despite the shorter attenuation time compared to VEPP-3, the observational data have a smaller spread, which we attribute to the better stability of the position of the center of mass of the beam in VEPP-2000.

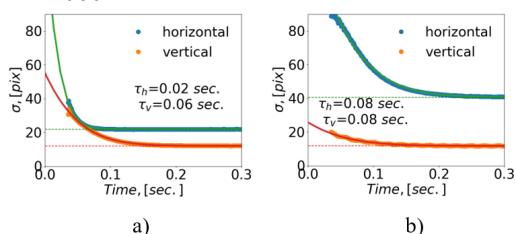


Figure 7: The dependences of the beam size change. Energy 405 MeV, where (a) for frequency 3 kHz higher than the equilibrium frequency, (b) for frequency 2 kHz below than the equilibrium frequency. The approximation was carried out by decreasing exponent.

According to the theoretical dependence and the developed measurement technique, the decrements (and thus the damping times) of the radial betatron oscillations were measured at VEPP-2000 at various revolution frequencies (Fig. 8).

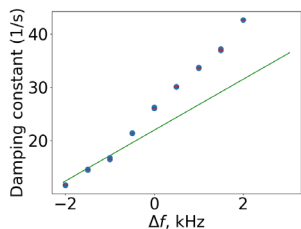


Figure 8: Dependence of the decrement and damping time of radial betatron oscillations at VEPP-2000 at a beam energy of 405 MeV. The standard (equilibrium) revolution frequency is 12292.5 kHz, and the horizontal axis shows the deviation from this frequency. (Blue is experiment, green is simulation).

SIMULATION

Radiation damping in the VEPP-3 storage ring was simulated using the Methodological Accelerator Design (MADX) [8] software code developed at CERN. Calculations were performed for beam energies of 428.6, 500, and 600 MeV at various revolution frequencies.

The results include plots illustrating the dependence of damping decrements and damping times on the revolution

frequency (Fig. 9). Analysis of the results shows that the decrements exhibit a linear dependence on frequency, which is consistent with theoretical expectations. A redistribution of the damping decrements is also observed: as the horizontal decrement increases, the values of the other two decrements decrease accordingly.

The simplest way to verify the correctness of the distribution of attenuation decrements by degrees of freedom is to apply Robinson's theorem. In our case, for all four energies, the simulation results are confirmed by Robinson's theorem with good accuracy.

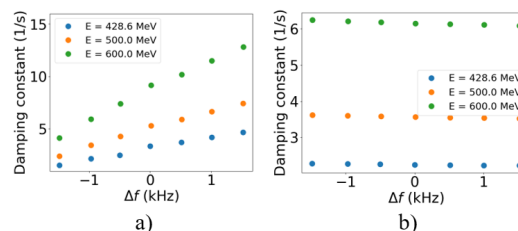


Figure 9: The modeled dependence of damping decrements and damping times on the revolution frequency for three energies: 428.6, 500 and 600 MeV: (a) horizontal; (b) vertical.

The same simulation approach was applied to the VEPP-2000. The outcome is displayed in Fig. 8. The obtained data indicate that in reality, the attenuation occurs faster than predicted by the simulation. The discrepancy between theory and experiment can be explained by unaccounted features of the VEPP-2000 magnetic structure or by differences between the accelerator model used for calculations and the actual machine.

CONCLUSION

Experimental values of radiation damping decrements for each energy are compared with model predictions. It is shown that the observed damping decrements are in good agreement with the model values obtained from the standard accelerator data model.

The deviations are within the limits of experimental errors and can be explained by inaccuracies in measuring the beam size, as well as possible additional sources of losses and disturbances in the system.

The data obtained can be used to calibrate beam dynamics models and optimize storage parameters.

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