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OBSERVATION OF SAW-TOOTH EFFECT ORBIT AT VEPP-4M COLLIDER

E. Bekhtenev, G. Karpov, D. Leshenok[1], S. Nikitin, O. Plotnikova, Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia
[1]also at Novosibirsk State University, 630090 Novosibirsk, Russia

Abstract

We study the relative position of the electron and positron closed orbits in the VEPP-4M single storage ring (see Fig. 1) collider in experiments on orbit precision monitoring. A difference in the orbits can affect the accuracy of several fundamental experiments, e.g. precise comparison of the electron and positron spin frequencies (the CPT invariance test) [1]. In this case, the spin precession frequencies of particles should be compared within at least $5\cdot10^{-9}$. The distinction of frequencies depends on the features of the radial orbits. Ideally, the difference in the electron and positron orbits is set only by distributed radiation losses of particle energy. The corresponding contribution to the total orbit distortions is called the Saw-Tooth effect orbit. Another example of possible precision experiment at VEPP-4M is search for the light speed anisotropy (LSA). In this case, it is necessary to ensure a stability of the difference in the radial orbits of electrons and positrons at a level of 1μm.

INTRODUCTION

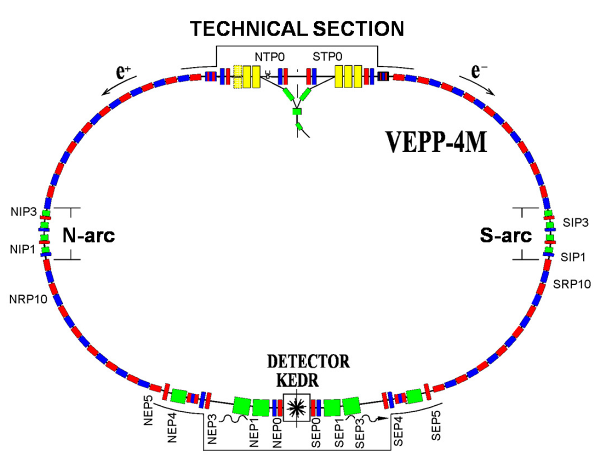

Figure 1: Positions of BPMs near four meeting places.

A new system of BPMs at VEPP-4M [2] allows observing differences in the orbits of beams within 10 μm, and higher accuracy can be achieved by averaging. So, the features of the daily observations of beams orbits can be explored with the same accuracy. These features may be important in the formulation of CPT experiment, as well as the determination of the threshold on the LSA magnitude.

To date, the accuracy of the comparison of the anomalous magnetic moment of electrons and positrons in a storage ring is 10^{-8} (the experiment at VEPP-2M) [3]. In experiments at the VEPP-4M collider [4], a record resolution in the frequency of resonant depolarization of $2\cdot10^{-9}$ [1] has been obtained, and the planned accuracy of direct comparison of electrons and positrons spin frequencies is $5\cdot10^{-9}$. That is why the study of the factors associated with the orbit and affecting the accuracy of the experiment is especially important.

BPM SYSTEM

There are 54 BPMs at the VEPP-4M collider. The BPM electronics can conduct both turn-by-turn and equilibrium-orbit measurements for all bunches moving in the collider. Measurements of the equilibrium orbit are made once per second for all bunches. The BPMs make turn-by-turn measurements with a frequency of 0.8 MHz. The equilibrium orbit is calculated by averaging the turn-by-turn data in a period of 20 ms (in the 50 Hz band). EPICS is used as a control system.

The main problem for achieving a required accuracy of a few tens of microns is the separation of BPM signals for electron and positron bunches. This problem has been solved in two ways: increasing the analog bandwidth to 200 MHz and digital compensation for overlapping of electron and positron signals. The wide bandwidth enables separation of measurements of electron and positron bunches with a time interval between bunches of up to 18 ns. The beam position is measured in each revolution [2].

Delay scanning with a step of 10 ps around the signal top in the range of ±40 ps is carried out for excluding the measurement error caused by the delay instability of different chips. After completing the scanning, the maximum signal for each channel is chosen. For reducing the measurement error caused by overlapping of the electron and positron signals, the program compensation for the signal "tail" is implemented in the system. The "tail" of the first bunch signal on the peak of second bunch signal at a time interval between the signals of ~18 ns is about 0.5-1%. Such a "tail" value without compensation can cause an error of up to 0.5 mm in measuring the position of the second bunch. The digital compensation decreases the position measurement error for the second bunch 3 to 5-fold.

CALCULATION OF SAW-TOOTH ORBIT

The Saw-Tooth orbit depends on the radiation losses per turn. The nature of the origin of such perturbations is clearly seen with an example of the VEPP-4M azimuthally homogeneous model. In this model, when the equivalent RF resonator, indicated by the Heaviside function $\mathcal{H}(s)$, is at the azimuth with s = 0, the motion equation for electrons and positrons in the median plane is

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$$x''(s) + \frac{\nu^2}{R^2}x(s) = \frac{U_0 K}{E}\left(\frac{1}{2} \mp \frac{s}{2\pi R} \pm \mathcal{H}(s - 2\pi R)\right), \quad (1)$$

where R is the radius of the orbit, $K=1/R$ is the rigidity of the focusing, ν is the frequency of betatron oscillations in the median plane, and U_0/E is the relative energy loss per revolution. The upper sign in the equation corresponds to electrons, and the lower sign corresponds to positrons. Figure 2 shows the positron orbit for azimuthally homogeneous model (red line) of VEPP-4M with parameters close to the real parameters of VEPP-4M:
R = 58 m, ν = 8.54, and $U_0/E \approx 177.073 \cdot 10^{-6}$. In a machine with mirror symmetry of the magnetic structure, these deviations for electrons and positrons will be mirror-symmetric.

However, if we talk about the CPT experiment, the violation of the mirror symmetry of the storage ring magnetic structure can lead to an additional error. This contribution was evaluated for the azimuthally homogeneous model of the VEPP-4M collider. The dispersion of the leading magnetic field values $\Delta H/H_0$ is equal to 10^{-3}; the radius R is equal to 38 m (the average radius of the bending magnets in the storage ring); E is equal 1.85 GeV. Then the difference in the average electron and positron energies is [5] $(\langle E_-\rangle - \langle E_+\rangle)/E \approx 2 \cdot 10^{-12}$.

The program MAD-8 was used to calculate the energy loss of electrons to radiation per full revolution in the storage ring of the VEPP-4M collider, only the sections containing bending magnets taken into account. It follows from the calculations that the energy loss per revolution is 30 keV at 1.85 GeV and 726 keV at 4.1 GeV.

Figure 2 shows a closed positron orbit at 4.1 GeV in the real structure of the VEPP-4M storage ring (green line) with five working RF resonators in the technical section [6]. The orbit is compared with the solution for the azimuthally homogeneous approximation of the VEPP-4M collider.

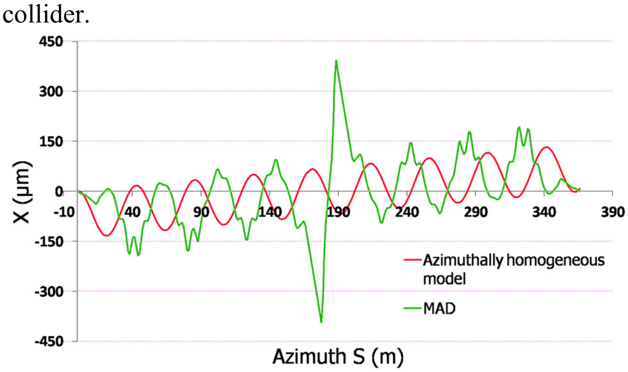

Figure 2: Positron orbits in azimuthally homogeneous model and those calculated by MAD for E = 4.1 GeV.

The main differences are concentrated in the experimental section (large beats of the beta function in the final focus lenses) and in the technical section (absence of magnets in close proximity to the resonators). For electrons the solution will be mirror-symmetric.

It can be seen from the graph that the maximum deviation of both electron and positron orbit from the equilibrium orbit is ~100 µm. Thus, it can be seen that the maximum value of the difference between the electron and positron orbits is ~1 mm, due to the large beats of the beta function in the final focus lenses. For a low energy E = 1.85 GeV this value is eight times smaller because the amplitude associated with energy losses increases as γ^3.

According to the calculations, the beam crossing angle in the detector KEDR due to the Saw-Tooth effect is not zero. Recalculated to the ϒ-meson production energy (2×4.73 GeV), it is $\theta = 2.23 \cdot 10^{-4}$ rad. Then the corresponding center-of-mass energy shift [7] $\Delta M/M = -\theta^2/8 \approx 10^{-8}$ is negligible. For comparison, the achievable energy measurement accuracy in the VEPP-4M experiment does not exceed 10^{-6}.

OBSERVATION OF SAW-TOOTH ORBIT ON VEPP-4M

The experiment was carried out at a maximum possible energy of 4.1 GeV. A five-hour run was performed to measure the beam orbits without changing the pairs of electron and positron bunches (2×2 mode) circulating simultaneously in the VEPP-4M ring. The spread of the every-second readings in each measured orbit is ± 30-40 µm. This gives a precision of ~1µm in 1 hour of observation. The instability of the average values is up to 50 µm. In these experiments, the electrostatic separation of the beam orbits was turned on at all parasitic interaction points (IPs) (centers of the south and north arcs (IP3 and IP2) and technical section (IP1)). Bunches met only at the main IP (IP0) (KEDR detector) [8] and were not separated there throughout the observation period.

Data from the BPMs evenly distributed over the storage ring were used to construct the differences in the orbits of electrons and positrons for all combinations of electron and positron bunches (e1-p1, e1-p2, e2-p2, e2-p1). See Fig. 3.

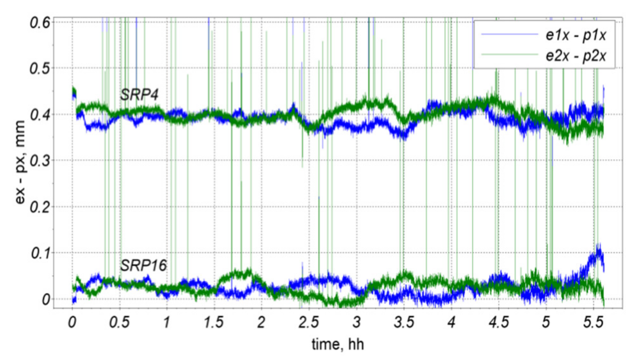

Figure 3: BPMs SRP4 and SRP16 at the beginning and end of the south arc: difference in the e^+e^- radial orbits in the first and second pairs of counter bunches.

The horizontal coordinate of the electron ("–") and positron ("+") bunches on the BPMs consists of several contributions: $\boldsymbol{X}^{\mp} = \boldsymbol{X}_R^{\mp} + \boldsymbol{X}_M^{\mp} + \boldsymbol{X}_Z^{\mp} + \boldsymbol{X}_E^{\mp} + \cdots$, where X_R is the deviation caused by the radiation loss, X_M is the contribution to the radial orbit due to perturbations of the magnetic structure, X_Z is the change associated with local coherent energy loss to chamber impedance, and X_E is the contribution of electrostatic fields. The difference be-

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tween the radial orbits of electrons and positrons is found as follows: $\Delta X = \Delta X_R + \Delta X_Z + \Delta X_E + \cdots$.

The difference in the orbits does not depend on the geometric "nulls" and the contribution of time-unstable magnetic disturbances. The latter are determined by the supply sources and the temperature dependence of the geometric parameters of the storage ring. Thus, results of observation of the difference between the electron and positron orbits contain the most precise information on factors that are important in conducting precision experiments.

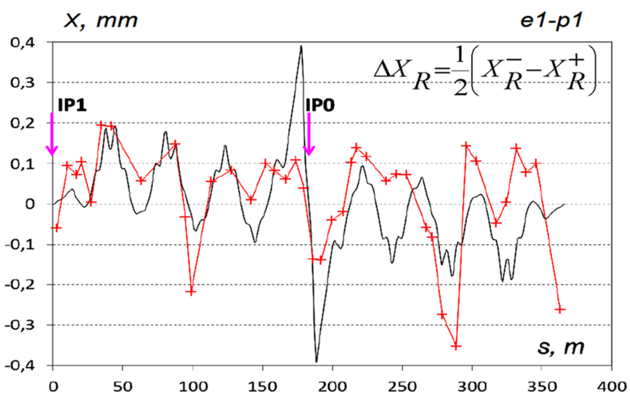

Figure 4: Difference between e^+e^- radial orbits, IP in this pair marked with arrows.

From comparative analysis (see Fig. 4) of all possible combinations of pairs of counter bunches, we can conclude that the behavior of the difference between the orbits of electrons and positrons is approximately the same for all pair combinations and coincides in phase with the calculated data. One can see noticeable deviations between the experimental dependence and the theoretical one in individual parts of the orbit, in particular, where BPMs are located near the IPs: IP0 and IP1.

According to analysis by the developers of the system of BPMs to measure the beam coordinates in each revolution, the main factors affecting the accuracy of comparison of electron and positron orbits are as follows:

1) Echo signals generated by a bunch on abrupt changes in the chamber size.

2) "Tails" of signals on BPMs located close to the IPs. The measurement error increases for the chronologically second bunch in a colliding pair.

3) The asymmetry of some BPMs design, which is due to the sensitivity of the sign of the direction of the particle velocity.

For minimizing the effect of the "tails" it is necessary to conduct an experiment in the 1×1 mode in two variants. In the first variant, the electron and positron beams meet at IP0 and IP1. And, in the second variant, the beams meet at IP2 and IP3. In this case, the areas with the least influence of the "tails" are longer than those in a 2×2 mode.

RESUME

The proposal [9] is devoted to an experiment on detecting the LSA. Under certain conditions, it could be realized at the VEPP-4M collider. The possibility of conducting the experiments depends on the stability of the measured difference in the electron and positron orbits. According to new preliminary estimates [10], in order to increase the accuracy in observing the LSA in comparison with the experiment in [11], the accuracy in comparing the electron and positron orbits in daily observations must be ~ 1μm and better. To answer the question of whether such stability exists, parallel monitoring of the electron and positron orbits with minimum effect of electrostatic separation systems and without meeting effects should be carried out. It may be the experiment with the 1×1 mode with the separation system turned off at all IPs.

Besides, it is necessary to conduct additional experiments in the 1×1 mode at an energy of 4.1 GeV and above to minimize the effects of the signal “tails”. It will be possible with a low beam current of ~3 mA and energy of 4.1 GeV and more. In these experiments, IPs with the separation system turned off will be changed.

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