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DYNAMIC APERTURE STUDY AT THE VEPP-4M STORAGE RING

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Abstract

Dynamic aperture has been studied experimentally at the VEPP-4M electron-positron collider. A transverse bunch motion was excited by fast kickers. The beam intensity and amplitude of the coherent oscillations were measured turn-by-turn by the BPM. In this paper the technique of determining the dynamic/physical aperture is described. Several methods of increasing the dynamic aperture are discussed. The results of computer simulation and simple model analytic prediction explaining the experimental data are presented.

1 Introduction

In [1] the results of the nonlinear phase trajectories and amplitude-dependent tune shift measurement in VEPP-4M are discussed. Here we concentrate on the aperture limitation study due to the nonlinear magnetic field.

The measurements were performed at the injection energy of 1.8 GeV with the following beam parameters [2]: horizontal emittance ϵ_x =35 nm, betatron tunes ν_x =8.620 and ν_z =7.572, natural chromaticity ξ_x =-13.6 and ξ_z =-20.6, revolution period τ =1.2 μs. Large contribution of the final focus quadrupoles to the natural chromaticity ($\simeq$50 % in the horizontal direction and $\simeq$ 60 % in the vertical direction) is compensated by the near-by sextupoles of $SES2$ and $NES2$ families (6 lenses). The residual chromaticity is corrected in the arcs by 32 sextupole corrections distributed along the dipole magnets (DS and FS families). Besides, there is quadratic nonlinearity produced by the magnets pole shape and qubic nonlinearity generated by the octupole field correction winding incorporated inside the bending magnet coils.

The dynamic aperture is measured by the coherent beam motion excitation [3], [4], [5]. Coherent betatron motion is excited by fast electromagnet kickers in the horizontal or vertical planes. The electrons/positrons separator $TU9$ is used as the horizontal kicker. It has a half-sine pulse with the duration of 50 ns and maximum amplitude of 30 kV. In the vertical direction the beam is kicked by the positron beam inflector with the pulse of 150 ns duration and 25 kV amplitude.

To measure the beam displacement and the intensity of every revolution BPM $SRP3$ in the turn-by-turn mode is used [6]. The are four digitizing channels equipped with the fast 10-bit ADCs with 100 ns sampling time and 4K words memory. The ADCs is triggered by the VEPP-4M kicker magnet trigger. The measured BPM resolution (rms) in this mode for the beam current range of 1-5 mA equals $\simeq$ 70 μm for both direction.

The kicked beam displacement versus the turn number is shown in Fig.1. One can see that during several thousands of revolutions when the measurements are made, coherent and radiation damping are quite negligible for the horizontal motion. But for the vertical one, where a strong electromagnetic beam interaction with the inflector electrodes exists, a fast damping is significant and has to be taken into account when the vertical aperture is measured.

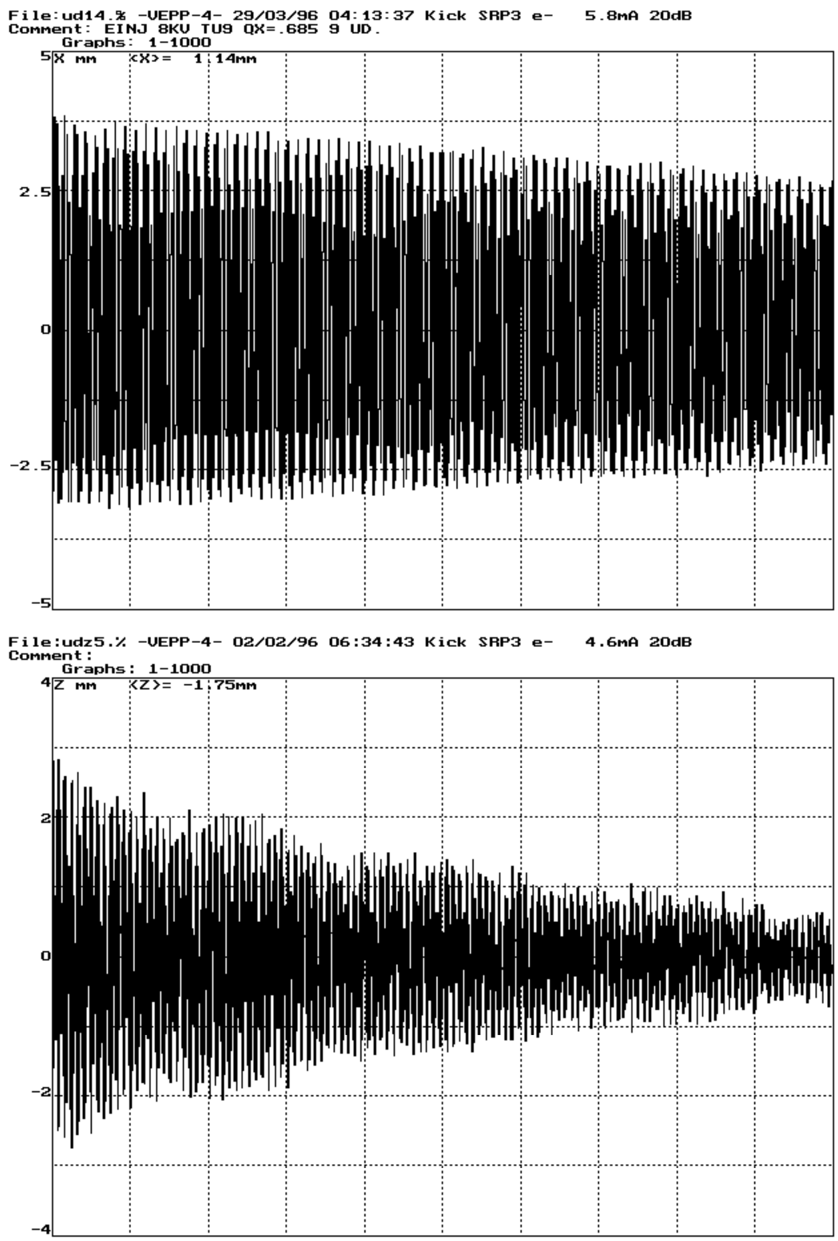

Figure 1: Horizontal (left) and vertical (right) beam displacement versus the turn number.

2 Dynamic aperture measurement technique

The measurement of the coherent beam motion allows to determine dynamic or physical aperture as a displacement at which the beam intensity loss occures - the same way it does in the computer tracking. But contrary to simulation where a single particle is tracked, in experiment, we deal with the beam of the finit size and current. The later can cause many effects (coherent and incoherent) which obscure the precise aperture measurement. Hence, the beam loss study has been carried out before performing a dynamic aperture measurement. We expected that the particles would be lost very fast outside the stable motion boundary because their amplitude is grows exponentially when the nonlinear motion becomes unstable.

This study shows that:

1. When the kick amplitude is low, the BPM does not indicate the intensity reduction: all particles move inside the acceptance along the stable trajectories.

2. At some intermediate kick amplitude a long term beam loss appears. In this period (about 10 ms) many effects (including damping) interfere with the measurements and it is very difficult to extract the figures relating to the aperture limitation.

3. And only starting with the high enough amplitude of the kick, a short time (20-50 turns) beam loss is observed (Fig.2). Only this loss corresponds to the dynamic aperture limitation because of the fast growth of the particle displacement outside the stable region.

Total intensity decreases include both long and short term parts but only the last one defines the aperture limitation unambiguously.

Apart from the beam intensity, the BPM also measures the position of the beam center of mass. The initial amplitude of the coherent oscillations is computed for the first 30 turns to cancel all damping effects. For low amplitudes, the BPM coordinate reading X_p linearly depends on the kick voltage $X_p = KU$. However, when the fast beam loss is observed, this dependence drastically declines from the linear one (Fig.3). To explain this fact we have assumed that the beam center of mass $X_p(U)$ just after the kick differs from the actual kick amplitude X_0 because some beam portion is lost and several dozens of revolutions are not enough for the quantum effects to restore the initial beam distribution. This fact has to be taken into account when the dynamic aperture is measured by BPM.

To verify our assumption, we consider the beam kicked onto the boundary of the dynamic or physical acceptance $A_x = a_x + X_0$ (see Fig.4). For the Gaussian distribution $\mathcal{P}(x, x')$ [7] with the rms beam size σ_x, the ratio of the beam intensity inside the stable phase area to the initial one $\kappa = I_1/I_0$ is given by the error function [8]

$$\kappa = 1/2 \pm \Phi(a_x/\sigma_x),$$
$$\Phi(A_x/\sigma_x) = \frac{1}{2} erf(\frac{a_x}{\sqrt{2}\sigma_x}),$$

where "+" ("-") is taken when $\kappa > 1/2$ ($\kappa < 1/2$). Assuming that $A_x >> \sigma_x$, we can integrate $\mathcal{P}(x, x')$ over x' from $-\infty$ to $+\infty$. After the beam distribution tail is lost outside the stable acceptance, the BPM coordinate is written as

$$Mx = \frac{\int_{-\infty}^{A_x} x\mathcal{P}(x)dx}{\int_{-\infty}^{A_x} \mathcal{P}(x)dx}.$$

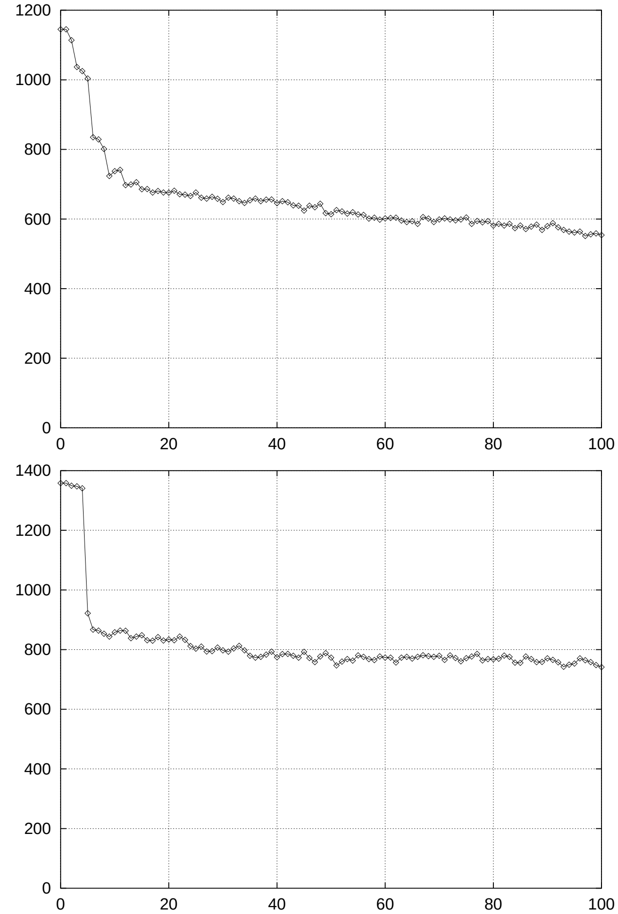

Figure 2: A fast beam loss onto the dynamic (upper) and physical (lower) aperture. First 100 revolutions are shown.

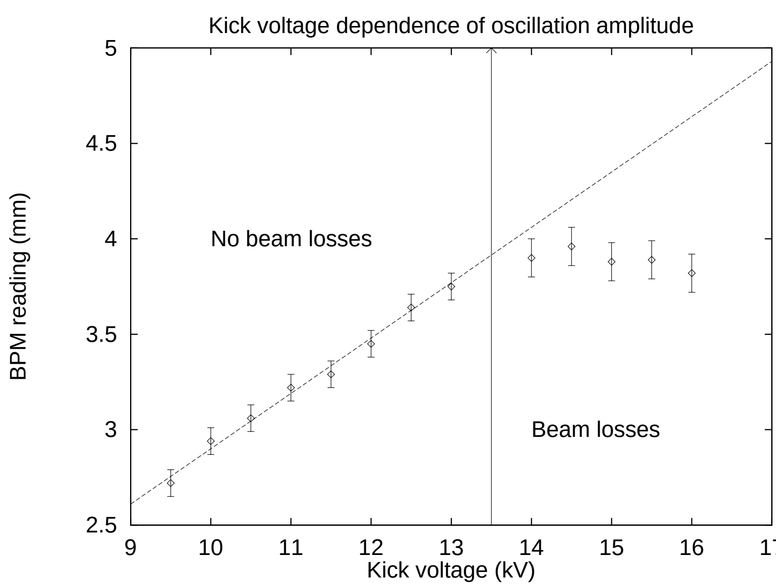

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Figure 3: BPM coordinate reading as a function of the kick voltage.

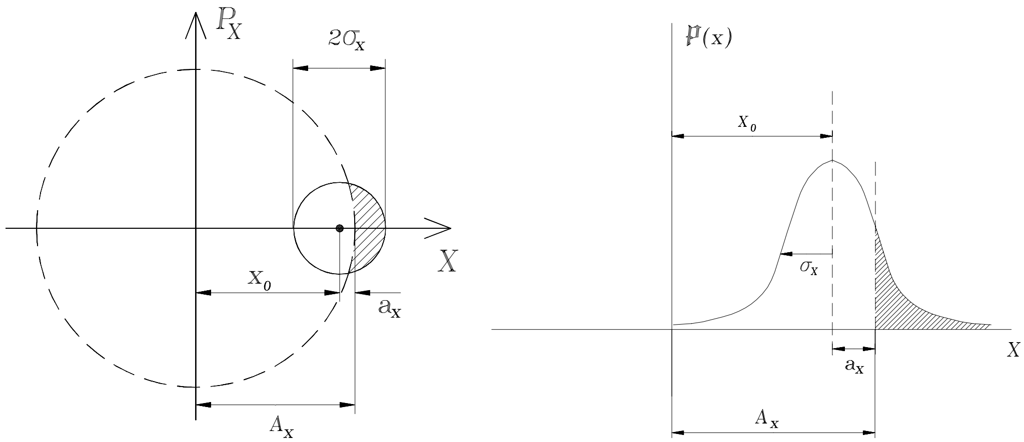

Figure 4: Beam kicked onto the boundary of the dynamic or physical acceptance (left - phase space, right - beam distribution).

The latter after some manipulations gives

$$X_p = X_0 - \sigma_x \frac{1}{\kappa\sqrt{2\pi}} \exp(-\frac{a_x^2}{2\sigma_x^2}) = X_0 - \sigma_x F(\kappa),$$

where $X_0 = KU$ is the linear kick amplitude. Knowing the value of κ, one can find $F(\kappa)$. In the reasonable range of $\kappa = 0.2 \div 1$, $F(\kappa)$ can be approximated as

$$F(\kappa) \simeq 1.6(1 - \kappa).$$

Fig. 5 shows the measured value of $\Delta X(\kappa) = X_0 - X_p(\kappa) = \sigma_x F(\kappa)$. The horizontal rms beam size extracted from these data $\sigma_x = 0.5 \pm 0.12$ mm corresponds quite well to that obtained

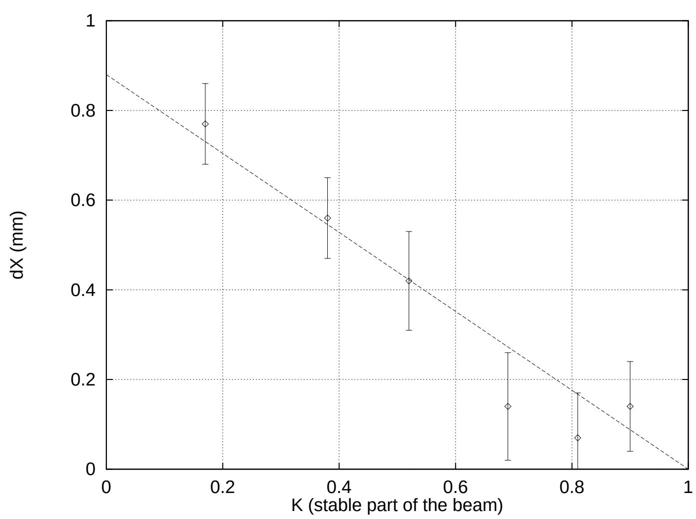

Figure 5: Measured dependence of $\Delta X(\kappa)$

by the beam lifetime measurements with the moovable scraper ($\sigma_x = 0.55$ mm). The accuracy of the BPM position measurement from kick to kick is determined mostly by the kicker stability and equals 5-7%.

From these measurements we can conclude that fast beam loss (for 20-50 beam revolutions) actually relates to the aperture limitation, while the long term beam intensity measurements can include many different effects. For the dynamic aperture measurement we proceed as follows:

1. The coefficient $K = X_p/U$ is found at the low kick amplitute.
2. The kick voltage is increased till the half beam is lost after the first 20 revolutions, $\kappa = I_{20}/I_0 \simeq 0.5$.
3. The dynamic aperture is defined according to $A_x = KU_{0.5}$.

For a typical VEPP-4M lattice at the injection energy, the measured aperture limitations at the azimuth of BPM station $SRP3$ are

$$A_x = 4.5 \text{ мм}, \quad A_z = 5.1 \text{ мм},$$
$$\sigma_x = 0.55 \text{ мм}, \quad \sigma_z = 0.42 \text{ мм},$$
$$\beta_x = 4 \text{ м}, \quad \beta_z = 12 \text{ м},$$

Now the question is how to distinguish which one aperture, dynamic or physical, limits the stable area? To answer this question we have measured the beam loss at the movable scraper. The scraper moves toward the beam orbit with the step as small as 0.1 mm and fast beam loss is studied. Fig.2 shows the beam loss without scraper and when the latter is inserted into the vacuum chamber. One can see that if the boundary of the motion is determined by the scaper, the beam intensity drops sharply during the first revolution, while for the dynamic aperture limitation several dozens of turns are required to get particles out of the stable area.

In case of VEPP-4M, we have dynamic aperture for the horizontal plane and physical aperture for the vertical plane.

3 Theory analysis

The VEPP-4M model lattice tracking demonstrates the horizontal dynamic aperture by a factor of 2 larger than the measured one.

To explain this descrepancy, we consider analytically the horizontal dynamic aperture in the vicinity of the resonance $3\nu = m$. This isolated resonance can be described with the following Hamiltonian,

$$H_r = \delta J_x + \alpha J_x^2 + f J_x^{3/2} cos 3\phi_x,$$

where J_x and ϕ_x is the action and angle variables, $\delta = \nu_x - m/3$ is the distance from the resonance, α is the nonlinearity, and f is the resonance driving term coresponding to the azimuthal Fourier harmonic of the sextupole perturbation A_3 as

$$f = 2\sqrt{2}A_3 = \frac{1}{12\sqrt{2}} \int_0^{2\pi} \beta_x^{3/2} \frac{B"}{B\rho} cos(3(\psi_x - \nu_x\theta) + m\theta) d\theta.$$

The action variable relates to the transverse displacement as $x(s) = \sqrt{2\beta_x(s)J_x}$. The contours of constant H_r are shown in Fig.6 in $x - p_x$ space. The stable motion is limited by two points which correspond to the action J_{x1} ($\phi_x = 0$) and J_{x2} ($\phi_x = \pi$). The first point is a resonance fixed point and can be found from

$$\frac{\partial H_r}{\partial J_x} = 0, \quad \frac{\partial H_r}{\partial \phi_x} = 0,$$

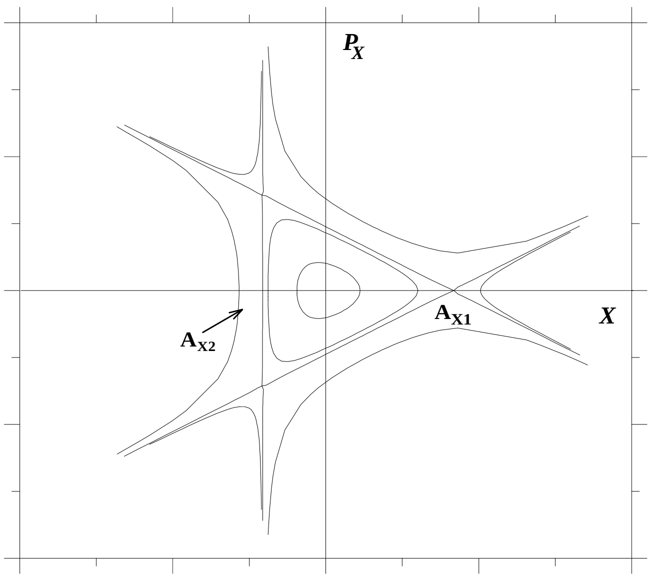

Figure 6: Phase space near the resonance $3\nu_x = m$.

which yields

$$J_{x1} = \tfrac{3f}{8\alpha}[(1 + \tfrac{32}{9}\tfrac{\delta\alpha}{f^2})^{1/2} - 1]. \quad (1)$$

The second point J_{x2} is defined by the invariant Hamiltonian $H_r(J_{x1}, 0) = H_r(J_{x2}, \pi)$ that gives the forth power equation which can be solved numerically.

To calculate the horizontal dynamic aperture from (1) we will use the experimental results presented in [1]:

1. For our tune point $\nu_x = 8.620$ the measured sextupole perturbation harmonic equals $A_3 \simeq -3.1$ m$^{-1/2}$. This value reasonably corresponds to the model one.
2. On the contrary, the measured nonlinearity that is much more larger than that obtained from VEPP-4M model lattice. The experimental data show $\Delta\nu_x/a_x^2 = \alpha/\beta_x = 8 \times 10^{-4}$ mm^{-2} which corresponds to $\alpha = 3200$ m^{-1} for $\beta_x = 4$ m. The study indicates the octupole field errors in the final focus quadrupoles (where the betatron functions reach the value more than 100 m) as a possible source of this nonlinearity.

Substituting these values into the equation (1), we can obtain the following dynamic aperture at the azimuth of BPM $SRP3$ ($\beta_x = 4$ m):

$$A_x = (+5.1\text{мм}, \quad -3.3\text{мм}). \quad (2)$$

The measured dynamic aperture ($A_x = 4.5$ mm) is obtained from the oscillations amplitude averaged over several dozens turns, hence to compare it with the theory result we need to take from (2) the mean absolute value which equals $A_x = 4.2$ mm. The ideal VEPP-4M lattice gives the aperture of $A_x = (+10\text{мм}, \quad -5\text{мм})$ that is significantly larger than the measured one.

Apart from the analytic estimation, computer tracking of the realistic lattice has been performed with the octupole field incorporated into the final focus quadrupoles to provide the measured detuning effect. The tracking results agree with theoretic results.

In Fig. 7 the ideal dynamic aperture is shown together with the measured and calculated values of the horizontal aperture. All data are presented for the center of the straight section where $\beta_x = 14$ m and $\beta_z = 3$ m.

4 Dynamic aperture increase

According to (1), we need to reduce either the resonance driving term $f = 2\sqrt{2}A_3$ or nonlinearity α to open the dynamic aperture. We have verified each of these ways as well as combined both of them.

As the strong final focus sextupoles $SES2$ and $NES2$ strongly contribute to the harmonic A_3, we have decreased their excitation current from 8.4 A to 4.3 A. The residual chromaticity was compensated by the distributed sextupole correctors in the arcs.

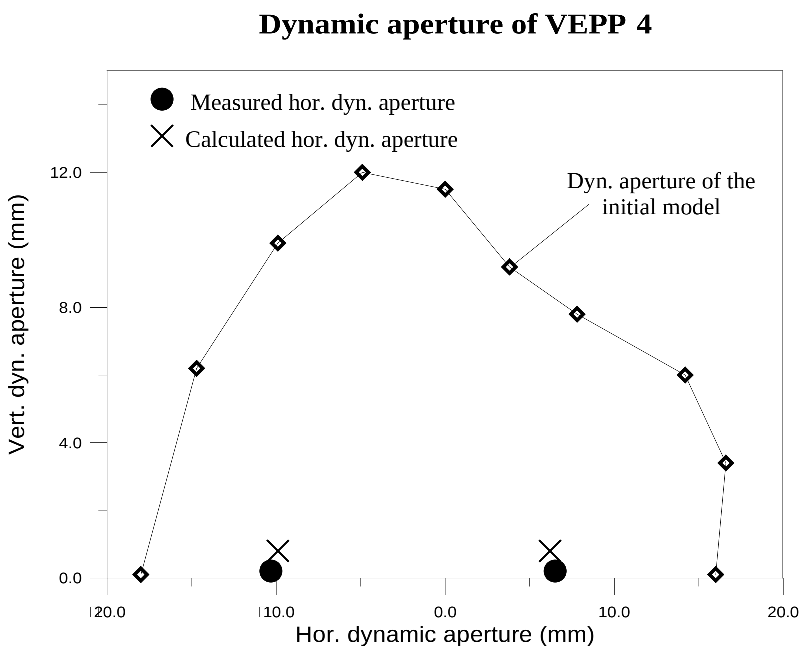

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Figure 7: Dynamic aperture of the VEPP-4M (ideal lattice, tracking). Measured and estimated (using measured nonlinearity) horizontal dynamic apertures are also shown.

As was shown in [1], in our case the horizontal nonlinearity is defined by the octupole perturbation. So, we have used the octupole coils in the arcs (which are not energized in the routine operation mode) to decrease the nonlinearity in a factor of 1.7.

The first way (sextupole harmonic reduction) results in the horizontal aperture enhancing up to 7 mm, which is more than 1.5 times larger than the initial one. On the contrary, the octupole corrections do not provide the significant aperture increase (5.4 mm). Measurements done after combining the two approaches indicate that the aperture increased up to 5.9 mm which is less than that obtained with the sextupol correction only.

The latter seems to be rather strange because the tracking for all three cases shows that the best result (up to 10 mm) is obtained in case when two kinds of corrections are used simultaneously. A possible explanation is that the octupole perturbation excites additional high order resonances which create obstacles to the aperture increasing. This discrepancy is a topic of continuing investigation. The simulation of the sextupole harmonic reduction corresponds quite well to the measurement results.

5 Conclusions

In conclusion, we have experimentally measured the dynamic aperture of the VEPP-4M storage ring. The measurements have been made by the turn by turn particle tracking system. As was found for VEPP-4M, the horizontal aperture is limited by nonlinear fields, while the vertical one is defined by the physical limitation.

The Hamiltonian for the particle motion was derived using the experimental data. The stable motion boundary, obtained with the single resonance approximation, shows good areement with the measurement results.

We have increased the horizontal aperture by the sextupole resonance driving term reduction. But we failed to do the same by the detuning compensation with the octupole field corrections.

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