EXPERIMENTAL STUDY OF IMPEDANCES AND INSTABILITIES AT THE VEPP-4M STORAGE RING

V.KISELEV, V.SMALUK, BINP, Novosibirsk, Russia

Abstract

Beam current at the VEPP-4M electron-positron collider is limited by transverse mode coupling (TMC) instability, occurred due to wake fields. Threshold current is decided mainly by transverse impedance of vacuum chamber. To study frequency dependence of the longitudinal and transverse impedances at the VEPP-4M, deviation of equilibrium RF phase and coherent betatron tune shift were measured in dependence of beam length. Impedance distribution along the ring was studied, using measurements of closed orbit in dependence of beam current. Instability evolution after injection was observed by a pickup using turn-by-turn measurement technique. Beam motion was also studied by computer simulation based on two particle model. Experimental results and results of the simulation are presented.

1 INTRODUCTION

The VEPP-4M is a 6 GeV racetrack electron-positron collider [1]. Relevant parameters of the VEPP-4M at the energy of 1.8 GeV are given in Table 1:

Table 1: The VEPP-4M parameters.

Circumference	P	366 m
Revolution frequency	f_0	818.936 kHz
RF harmonic number	q	222
Betatron tunes	Q_x/Q_y	8.560/7.620
Synchrotron frequency	ν_s	0.006÷0.03
Compaction factor	α	0.017
Damping times	$\tau_x/\tau_y/\tau_s$	35/70/70 msec
RMS bunch length	σ_s	0.025÷0.12 m
Aperture in semirings	$2a_x \times 2a_y$	0.06×0.03 m^2

To get a design luminosity at energy 5 GeV, the beam current is to be more than 20 mA in one bunch. But it was discovered that the captured current had threshold around 12 mA. Current limitation is due to TMC instability of vertical betatron oscillations, which causes large coherent shift of betatron frequency.

A feedback system for suppress this instability has been developed [2]. The system provides increase the captured current up to 25 mA.

2 TMC INSTABILITY

For beam motion analysis, when the TMC instability occurs, two particle model was used. The beam was considered as two macro-particles: head and tail.

In the first half period of synchrotron oscillation, the head (1-st) particle excites by its wake fields transverse oscillations of the tail (2-nd) one.

Equations of motion for both particles are [3]:

$$y_1''+2\alpha\cdot y_1'+Q_y^2\cdot y_1=0,$$
$$y_2''+2\alpha\cdot y_2' +Q_y^2\cdot y_2=ky_1\cdot\cos(2\pi\nu_s\theta), \qquad (1)$$
$$y'=dy/d\theta, \qquad \alpha=\delta/\omega_0, \qquad k=\pi/2\cdot\Delta Q_c\cdot Q_y,$$

where δ is damping decrement, ΔQ_c is coherent shit of betatron tune, $\theta=\omega_0 t$. In the second half period of synchrotron oscillation, particles interchange by its leading and trailing roles so the equations should be interchanged also.

The oscillation amplitudes of the head/tail particle and of the center of mass in dependence of beam current are given on Fig.1. These data were obtained by numerical solution of the equations (1) with the $y_1'(0)=y_2'(0)=0$, $y_1(0)=y_2(0)=y_0$ initial conditions and with various parameter ΔQ_c proportional to beam intensity.

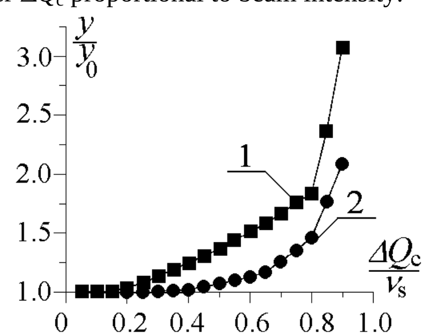

Figure 1: Oscillation amplitudes.
1-head/tail, 2- center of mass.

Note, that oscillation amplitudes of the head/tail particle, which decide the transverse beam size, increase with current more rapid than amplitude of the center of mass. The current threshold is reached when $\Delta Q_c \geq 0.8\nu_s$.

At the VEPP-4M, beam motion, when average current $\bar{I}$ of injected beam exceeds the threshold, is illustrated by Fig.2. Bunch length σ_s of the injected beam was made twice more than the equilibrium one. When the bunch length has been decreasing due to radiation damping, amplitude value of the beam current $I_a = \bar{I}\cdot P/\sqrt{2\pi}\sigma_s$ reaches the threshold, and the TMC instability occurs and causes beam losses.

Beam current and vertical center of mass position, measured by pickup during 1600 turns since 100 ms after injection, are shown on Fig.2*a*. One can see coherent betatron oscillations and beam losses occurring at the same time. Computer simulation given on Fig.2*b* makes clear the reason of the beam losses. Turn-by-turn vertical position $y_{C.M.}$ of the center of mass, y_1 of the head, and y_2 of the tail, are plotted. One can see that oscillation amplitudes of head and tail twice exceed the center of mass amplitude, which can be measured by pickup, and just these head/tail oscillations which increase the transverse beam size, cause the loss of transverse distribution periphery electrons.

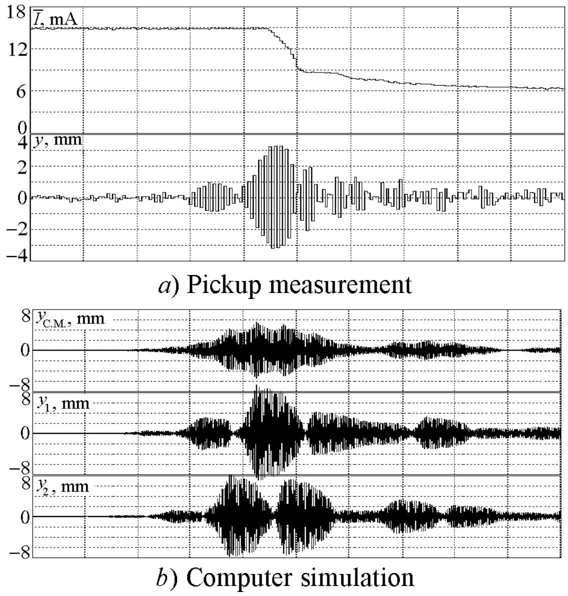

Figure 2: Developing of TMC instability.

3 IMPEDANCE CALCULATION AND MEASUREMENT

An impedance approach is used to analyze the interaction between beam and wake fields. The vacuum chamber components are considered as frequency-depended impedances.

For the VEPP-4M, impedance is formed mainly by about 50 inhomogeneities of the vacuum chamber. There are 16 vertical and 3 radial separators (pairs of strip-lines matched to 50 Ω through capacitor), resonance cavities, and sharp cross-section changes. Analytical expressions [4] can be used for impedance calculation for these simple cases. Calculations give a possibility to evaluate both a total value of the impedance and the impedance distribution along the ring.

All measurements described below were carried out in a vertical plain, as the vertical size of the vacuum chamber is less than the horizontal one, and the TMC instability is caused practically by the vertical transverse impedance only.

3.1 Longitudinal impedance.

The longitudinal impedance has both resistive and reactive components. The resistive component results in beam energy losses. Total longitudinal loss factor K_L was obtained by measurement of current-dependent shift of equilibrium RF phase $\Delta\varphi_s/\Delta\bar{I}$:

$$K_L = f_0 \cdot U_{RF} \cdot \cos\varphi_s \cdot \Delta\varphi_s/\Delta\bar{I}. \qquad (2)$$

For the VEPP-4M, the reactive component of the longitudinal impedance is inductive, as the bunch length σ_s exceeds considerably the vacuum chamber vertical size a_y. Inductive longitudinal impedance results in bunch lengthening. Thus, the normalized impedance $|Z_{\|}/n|$ can be calculated with the expression [5]:

$$\sigma_s^3 - \sigma_{s0}^2\sigma_s = \frac{\sqrt{2\pi}\cdot\bar{I}\cdot\left|\frac{Z_{\|}}{n}\right|\cdot R^3}{qU_{RF}\cos\varphi_s}, \qquad (3)$$

using measured σ_s, $\bar{I}$, and RF parameters, and calculated r.m.s. bunch length at zero current σ_{s0}.

Measured values of the longitudinal loss factor K_L and the normalized impedance $|Z_{\|}/n|$ in dependence of bunch length σ_s are given on Fig.3.

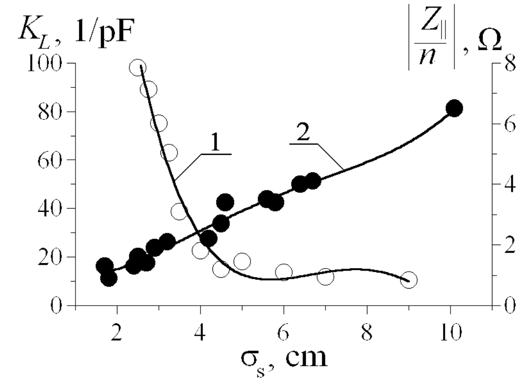

Figure 3: Longitudinal loss factor (1) and impedance (2).

3.2 Transverse impedance.

Transverse impedance of the VEPP-4M has also both reactive and resistive components, the resistive one causes fast damping of betatron oscillations. One can calculate decrement of the damping with the formula [4]:

$$\delta_Z = \frac{\bar{I}\cdot Z_\perp \xi_y c}{8\cdot(E/e)\cdot Q_y^2\alpha}, \qquad (4)$$

where $Z_\perp$ is the impedance, $\xi_y=\Delta Q_y/(\Delta p/p)$ is chromaticity. For the VEPP-4M, the measured values of vertical and horizontal decrements are shown on Fig.4 in dependence of the chromaticity, for beam current $\bar{I}$=7 mA, energy E=1.8 GeV.

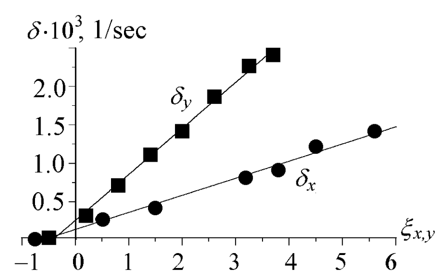

Figure 4: Fast damping decrement.

For ξ_y=0, decrement is determined by strip-lines. Decrement value for N pairs of matched strip-lines can be calculated using the expression:

$$\delta_L = I_a \cdot \sum_{i=1}^{N} \frac{\rho_i L_i}{d_i}\cdot\frac{f_0}{(E/e)}, \qquad (5)$$

where L_i and ρ_i are length and wave impedance of each strip-line of the pair i, d_i is a distance between the strip-lines.

Resistive component of the VEPP-4M transverse impedance, calculated using these measurements is $Z_{\perp}\cong 3.5$ MΩ/m.

Reactive component of transverse impedance results in coherent shift of betatron tune. Tune shift can be evaluated using the formula for a small betatron detuning caused by additional defocusing force:

$$\Delta Q = -\frac{1}{4\pi}\cdot\frac{\Delta Gl}{(H\rho)}\cdot\beta\,. \tag{6}$$

In frameworks of two particle model, one can use an expression for betatron detuning caused by transverse impedance:

$$\Delta Q = -\frac{1}{8\pi}\cdot\frac{I_a \cdot <Z_{\perp}\cdot\beta>}{(E/e)}\,, \tag{7}$$

where $<Z_{\perp}\cdot\beta>$ is the impedance averaged with β weight factor, β is beta function at the impedance location.

For the VEPP-4M, measured coherent shift of vertical betatron tune is $\Delta Q_c/\Delta I_a \cong 4\div 6\cdot 10^{-4}$, when $\sigma_s=3\div 9$ cm. Total value of $<Z_{\perp}\cdot\beta>\cong 22$ MΩ.

A model impedance distribution was calculated using the formulae for simple electromagnetic structures [4] placed at hypothesized locations of the impedance. To test the model distribution, two experiments had been carried out.

The first one is based on measurement of coherent tune shift deviation in dependence of beta function perturbation. The final focus quadrupole magnet EL1 placed close to the interaction point, was used for beta perturbation.

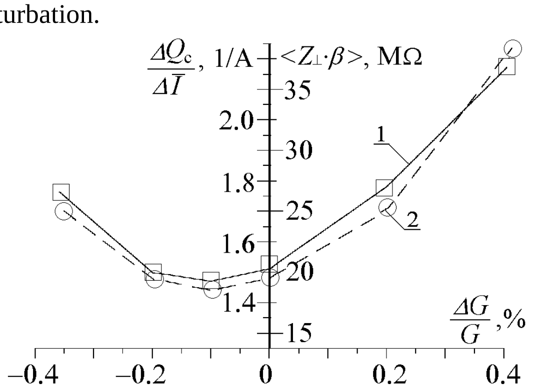

Figure 5: Measured $\Delta Q_c/\Delta \bar{I}$ (1), calculated $<Z_{\perp}\cdot\beta>$ (2).

Fig.5 shows the tune shift deviation, depended on the EL1 gradient, in comparison with $<Z_{\perp}\cdot\beta>$ calculated using measured perturbed beta function at the hypothesized locations of the impedance. Closeness of both curves means that the model impedance distribution is acceptable.

One more test of the model impedance distribution is based on measurement of closed orbit deviation due to additional defocusing force. According to the expression (6), one can consider a local transverse impedance as a defocusing quadrupole magnet, srenghth of which depends on beam current. When the beam position in the magnet is non-zero, the beam trajectory angle gets increase on θ_i:

$$\theta_i = \frac{I_a \cdot Z_{\perp i}}{2(E/e)}\cdot y_{0i}\,. \tag{8}$$

If a local bump of closed orbit has been created just at the impedance location, then the orbit deviation appears while varying the beam current. The orbit deviation is proportional to the local impedance $Z_{\perp i}$, current difference $\Delta\bar{I}$, and the bump amplitude y_{0i}:

$$y(s) = \frac{\Delta\bar{I}\cdot Z_{\perp i}}{4\sin\pi Q_y}\cdot\sqrt{\beta_i\cdot\beta_s}\cdot y_{0i}\,, \tag{9}$$

Due to finite length of orbit bump, only a total value of the impedance distributed along the bump can be measured. Lets suppose the distribution of impedance within the bump is uniform, and introduce specific impedance $\Delta<Z_{\perp}\cdot\beta>/\Delta s$, where Δs is the bump length. The value of the specific impedance is some average electromagnetic characteristic of the vacuum chamber section.

For the VEPP-4M, the impedance distribution measured using this method is shown on Fig.6.

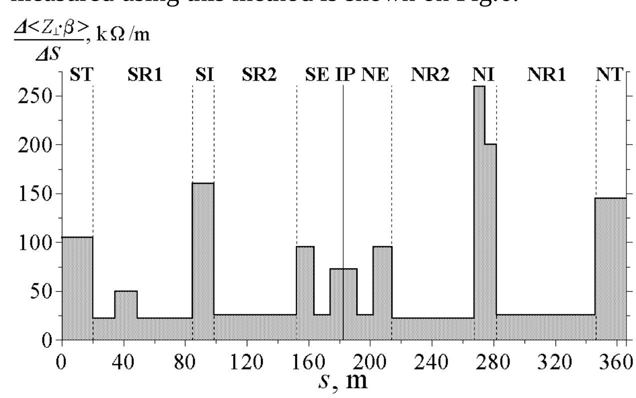

Figure 6: Measured impedance distribution.

ACKNOWLEDGMENT

We wish to thank E.Perevedentsev, G.Kurkin, N.Zinevich, A.Kalinin and E.Bechtenev for useful discussions and for help with beam measurements.

REFERENCES

1. V.Anashin et al. VEPP-4M Collider: Status and Plans. / These Proceedings.

2. M.M.Karliner et al. The Feedback System for Elimination the Fast Head-tail Instability at Storage Ring VEPP-4M. / Proc. of EPAC-96

3. PEP Group. Comparison between experimental and theoretical results for the fast head-tail instability in PEP. / Proc. of the 12-th Int. Conf. High Energy Accel., Fermilab, 1983, p.209-211.

4. Chao A.W. Physics of collective beam instabilities in high energy accelerators. / John Wiley & Sons, Inc., 1993.

5. B.Zotter. CERN/ISR-TH/78-16, 1978.