Collective Effects in the VEPP-3 Storage Ring

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Abstract

Lengthening of a single bunch has been investigated in the VEPP-3 storage ring at different energies for beam current up to 100 mA. The bunch length was measured using optical diagnostic system. The current dependences of the transverse beam size, synchronous phase shift, coherent and incoherent synchrotron tune shift have been measured. The experimental data are in agreement with the model of longitudinal potential well distortion. The real and imaginary parts of the longitudinal coupling impedance are deduced from measured data.

I. INTRODUCTION

The VEPP-3 storage ring is a 2 GeV electron and positron storage ring, which is multiamed facility [1]. This storage ring is operating with routine current up to 100...150 mA.

Two RF systems – at 2nd and 18th harmonics of a revolution frequency – are used at the VEPP-3 operation. The injection of particles takes place when the first one is working. The injection energy is 350 MeV. At the energy of 600 MeV, the second RF system is switched on to provide the acceleration of particles to the energy of experiment and to compensate synchrotron radiation energy losses. The maximum RF voltage is equal to 600 kV. During the experiment the 2nd harmonic cavity stays passive.

The bunch lengthening and incoherent synchrotron tune shift in the VEPP-3 storage ring has been measured [2], but that experiments was made only at injection energy and with low value of 1st harmonic RF voltage.

In this paper we present the measurements of collective effects, i.e. current dependences of the bunch length, width, synchronous phase shift and coherent and incoherent synchrotron tune shifts at the beam energies of 600, 1200 and 2000 MeV and at the maximum RF voltage.

II. INSTRUMENTATION AND RESULTS

The applied method for observation of beam parameters is based on using of a synchrotron radiations light emitted by the bunch of charged particles at one of the bending magnets [3]. We used two dissectors: for measuring longitudinal and transverse profile of a beam.

To decrease the statistical spread, the results of 16 measurements are accumulated and averaged at the each current point. The longitudinal resolution is 13 mm. This value have been obtained by measuring dependence of a beam length on RF voltage at a low current (less than 100 μA). One has to obtain a voltage dependence of a beam length at this current value like square root. The transverse resolution less than 0.17 mm has been obtained.

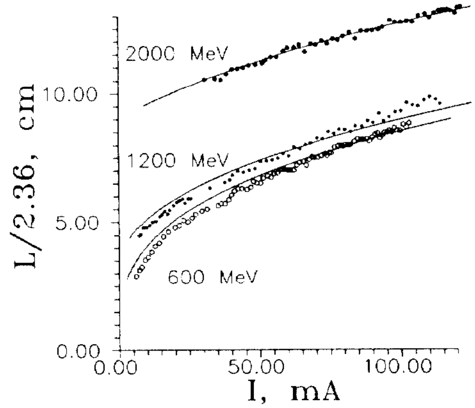

Figure 1: Bunch length versus current (L - halfwidth bunch length, $s = L/2.56$).

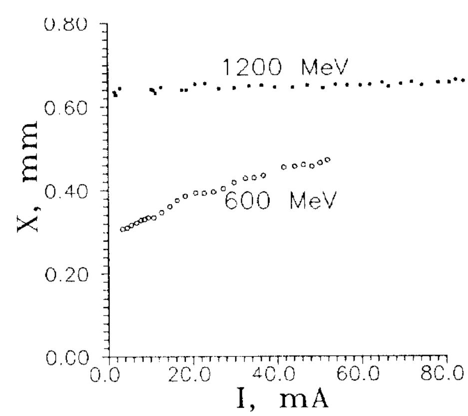

Figure 2: Current dependence bunch horizontal transverse size.

A. Bunch lengthening measurements

In Table 1 measured zero current length of a bunch at different energies is presented. The current dependence of bunch length at these energies is shown in Figure 1.

Table 1
Bunch length at zero current

Beam energy	MeV	600	1200	2000
rms bunch length	cm	1.4	3.8	9.0

The bunch length may increase due to different mechanisms with increasing of a beam intensity. At low energies beam transverse and longitudinal sizes could increase due

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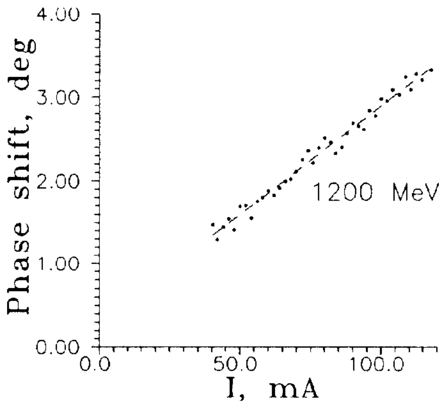

Figure 3: Current dependence synchronous phase shift.

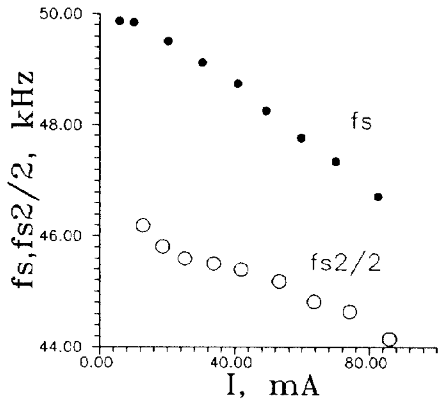

Figure 4: Current dependence synchrotron frequencies at 600 MeV.

to intrabeam scattering effect, which is suppressed at high energy with the law: σ_ϵ, $\sigma_x \sim 1/\gamma$, where $\sigma_\epsilon = \sigma_E/E$ is the energy spread, σ_x - the horizontal beam size, and γ - the relativistic factor. At a high current, the beam length increases due to potential well distortion and so called microwave instability. The behavior of a bunch lengthening due to potential well distortion can be described as [4]

$$\left(\frac{\sigma_l}{\sigma_{lo}}\right)^3 - \frac{\sigma_l}{\sigma_{lo}} = \frac{\sqrt{2\pi} I_o \mid Z_n/n \mid}{qU_o} \left(\frac{R}{\sigma_{lo}}\right)^3, \qquad (1)$$

where I_o is the average beam current, q is the RF harmonic number, U_o is accelerating voltage, $\mid Z_n/n \mid$ is the longitudinal coupling impedance at the n-th harmonic number of the revolution frequency, R is the mean radius of the ring, and σ_{lo} is the beam length at zero current. In the case of potential well distortion there is no increase of energy spread but incoherent synchrotron tune shift can be very large.

On the other hand, the bunch lengthening due to microwave instability is accompanied by energy spread increasing. For the case $\mid Z_n/n \mid$ has no frequency dependence (pure inductance), we have scaling low [5] $\sigma_l \sim I^{1/3}$ above threshold current of instability.

The value of longitudinal coupling impedance at the n-th harmonic of the revolution frequency, determined by the eq. (1), is equal to 11.3 Ohm at 600 MeV. At energies of 1200 and 2000 MeV these values are equal to 12.1 and 15.4 Ohm respectively. Besides we observed a length dependence of the value $\mid Z_n/n \mid$. The continuous curves in Figure 1 correspond to a theoretical dependence, determined by (1) for given values of an impedance. Note, no microwave instability threshold current was noticed.

At low currents the bunch has gaussian longitudinal shape. At high currents the bunch longitudinal shape changes from Gaussian to parabolic profile. Besides an asymmetry of bunch shape takes place. This asymmetry could be provided by the contribution of real part of impedance.

B. Bunch energy spread measurement

To obtain an information about energy spread, we measured a current dependence of bunch horizontal transverse size. But this value is determined by both betatron and synchrotron bunch sizes. In our case the betatron horizontal size is a little bit larger than the synchrotron one at the point of light emitting. In Figure 2 the current dependence of bunch horizontal transverse size is shown. At the energy of 1200 Mev (and 2000 MeV, which case is not presented at this graph) there is no change of a bunch transverse size. At the energy of 600 MeV there is a weak changing of this value with the current. Computer simulation shows that this dependence could be provided by the intrabeam scattering effect (for given bunch length current dependence).

C. Synchronous phase shift measurement

The synchronous phase shift is being determined as a difference between phase of beam longitudinal distribution center of mass and phase of RF system reference signal. The phase difference between reference signal phase and RF cavity phase is kept constant by phase feedback system. The accuracy is less than 0.1 degree.

The measurements of synchronous phase shift were done for energies of 1200 and 2000 MeV and results coincide. At the energy of 600 Mev this measurement haven't be obtained, probably due to phase oscillation of a beam. The results are shown in Figure 3. Experimental data allowed to determine a value of a bunch coherent energy loss. At current 100 mA this value is equal to 35 kV. This corresponds to the real part of impedance $R = Re \mid Z_n \mid = 1300$ Ohm.

D. Synchrotron tune shift measurement

It is possible to obtain some information about incoherent synchrotron tune shift by observing the behavior of longitudinal quadrupole mode frequency. In these experiments we excited dipole and quadrupole mode oscillations by phase and amplitude modulation of RF voltage, and then observed a response from a beam position monitor.

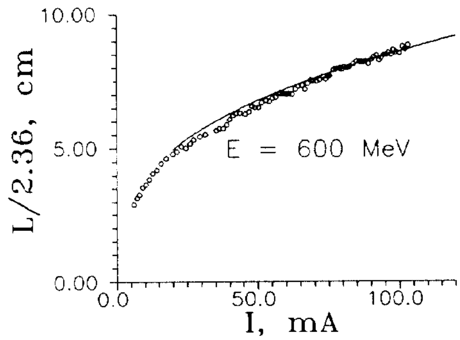

Figure 5: Calculated current dependence bunch length.

In Figure 4 the current dependence of the frequencies of dipole and quadrupole synchrotron modes at energy of 600 MeV are presented. We see that both the quadrupole and dipole modes frequencies decrease, and tune shift for the quadrupole mode is more than 10% at current 80 mA. At energy of 600 MeV we couldn't measure a quadrupole mode shift at current less than 10 mA because of exiting the coherent phase oscillations.

III. ANALYSIS

When the bunch wake fields damp during one revolution period, we have so called broad band impedance, which is provided by different discontinuities of a vacuum chamber. Otherwise, when the bunch interacts with self-fields supplied by the elements, having high quality factor Q, say about narrow band impedance. In our experiment the bunch lengthening was insensitive to the position of the cavity higher order modes tuners (apart from narrow bands where we observed coherent longitudinal instabilities) and to the position of the passive cavity tuner. So we conclude only single turn effects take place, which are described by broad band impedance model.

In the Figure 1 we see there is no good agreement of experimental data with the theoretical curve, calculated using eq. (1). Besides the bunch length arises steeper than 1/3 power of a beam current at energies 600 and 1200 MeV, provided pure inductive impedance. We suppose both parts of impedance – inductance and resistance – contribute the potential well distortion. To analyze beam lengthening due to potential well distortion we solved balance equation using a condition of full compensation of external RF voltage by fields produced of a bunch itself. For this condition the potential well has a flat bottom for all bunch lengths. The analysis of stability with this condition have been done at [6]. Let L and R are the inductive and the resistive parts of effective longitudinal coupling impedance. Equations for potential, produced a bunch itself is given:

$$L\frac{dI(t)}{dt} + RI(t) = U_s(t), \quad where \quad U_s = -q\omega_o U_o t. \qquad (2)$$

Here and further ω_o is the revolution frequency, $\tau = L/R$, t_h, t_t - the displacement of a head and a tail of a bunch, N - number of particles, e - the electron charge. Let $\Delta = (t_t - t_h)$ is the bunch length and $t_m = \frac{1}{2}(t_t + t_h)$ is the bunch mass center displacement (for simplification we ignore here the bunch shape asymmetry). Using boundary condition for the bunch tail we get an equation for bunch length current dependence, which can be solved numerically:

$$\Delta = 2 \cdot \left(\frac{T^2}{\Delta} + \tau - \left(\tau + \frac{\Delta}{2} + \frac{T^2}{\Delta}\right) \cdot exp\left(-\frac{\Delta}{\tau}\right)\right), \qquad (3)$$

where $T^2 = \frac{RNe}{q\omega U_o}$. Equation (3) describes quite correctly a bunch behavior for strong lengthening case, when it is possible to ignore zero current bunch longitudinal size (so called case of the frozen bunch [6]). In Figure 5 the calculated curve of a bunch length current dependence for R = 1300 Ohm and L = 600 nH (continuous curve) together with the experimental data points at the energy 600 MeV are presented.

IV. CONCLUSIONS

The current dependence of bunch length was measured. This dependence is in a quite good agreement with that obtained from solution of balance equation if real and imaginary parts of broad band impedance are of the same order.

Also a change of the bunch longitudinal shape has been observed. To separate the single turn (broad band impedance) and multiturn effects, the current dependence of bunch length was measured at different positions of both cavities tuners and no difference of bunch lengthening have been observed. Hence observed effects are single turn ones.

V. ACKNOWLEDGMENTS

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