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THE BUNCH SIZE MEASUREMENTS IN THE STORAGE RING SIBERIA-2

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Abstract

An interaction of particles with each other and electromagnetic fields produced by an external source and the bunch in the vacuum chamber defines the electron bunch sizes in the storage ring. To research the influence of the bunch-chamber interaction on the longitudinal motion of electrons and to estimate the relative contribution of the observed effects, the measurements of bunch sizes and a bunch current spectrum were carried out in the storage ring SIBERIA-2. Results of measurements and analytical estimations are presented at this article.

INTRODUCTION

The SIBERIA-2 works in the multi-bunch mode at the beam energy 2.5 GeV. The injection energy of electrons is 450 MeV. It is at this energy the effects of the particles interaction and the beam-chamber interaction are manifest due to weak radiation damping. Therefore research of longitudinal beam dynamics was started when there is a single bunch at the energy 450 MeV in the storage ring.

The bunch size measurements were carried out with the help of the optical observation station [1]. The beam spectrum was measured by a digital spectrum analyzer. The analytical estimations of the bunch sizes due to the multiple intra-beam scattering (IBS) and the potential well distortion effect were done in addition to measurements. Calculation of bunch sizes given by the IBS was made in ZAP [2].

EFFECTS AND BUNCH SIZES

The electron bunch has the Gaussian stationary distribution of particles in the synchrotron and betatron phase spaces. Bunch sizes are defined by a set of effects such as the quantum excitation, the radiation damping, the IBS and interaction with the wake-fields.

Classical and statistical approaches to consideration of the synchrotron radiation give the expressions to define zero current rms bunch sizes in the longitudinal and horizontal directions, respectively:

$$\sigma_{lo} = \frac{c\eta}{\omega_{so}} \frac{\sigma_{E\gamma}}{E}, \quad (1)$$

$$\sigma_x = \sqrt{\beta_x \epsilon_x + \left(D_x \frac{\sigma_{E\gamma}}{E}\right)^2}, \quad (2)$$

where $\frac{\sigma_{E\gamma}}{E}$ and ϵ_x – the equilibrium relative energy spread and the horizontal emittance given by the radiation damping and quantum fluctuations of the radiation [3], β_x и D_x – the horizontal beta-function and the dispersion of the storage ring, $\eta = \alpha - 1/\gamma^2$, α – the momentum compaction factor, E – the particle energy, ω_{so} – the incoherent synchrotron frequency given by the accelerating RF-field.

Weak collisions of particles inside the bunch lead to the excitation of betatron and synchrotron oscillations, to an increase of the energy spread and sizes of the bunch. The balance between the radiation damping and the IBS limits the growth of the bunch parameters. The effect depends on the number of electrons in the bunch. The current dependence of the energy spread and bunch sizes can be found numerically, because of the calculation formulas have the complicated form. One of the basic approaches to solving the problem of the IBS proposed by J.D. Bjorken and S.K. Mtingwa [4] and developed by M. Conte and M. Martini [5] was used by M.S. Zisman and his colleagues in ZAP.

The electromagnetic (EM) fields induced in the vacuum chamber by the electron bunch distort the shape of the potential well created by the external accelerating field and can lead to the significant increase of an amplitude of coherent oscillations and to the loss of stability of the particles motion, to the microwave instability and the turbulent increase of the bunch sizes.

The consequence of the potential well distortion is the change of the longitudinal size of the bunch. It can increase or decrease with increasing the number of electrons in the bunch, depending on the spectrum of interacting fields. As a rule, the longitudinal size increases with increasing the electron current in the storage rings, what is determined by the high frequency spectrum of the EM-fields. Their wavelengths are comparable and larger than the length of the bunch. In this case, the dependence of the longitudinal size on the bunch current is usually found from the system of equations [6]:

$$\begin{cases} \omega_s^2 - \omega_{so}^2 = \frac{e\eta\omega_o}{\beta^2 T_o E} I_b \frac{\sqrt{2\pi}}{(\omega_o \sigma_\tau)^3} Z_{eff}, \\ \sigma_\tau \omega_s = \sigma_{\tau o} \omega_{so} \end{cases} \quad (3)$$

where ω_s and σ_τ – the incoherent synchrotron frequency and the rms longitudinal duration given by the potential well distortion effect, $\sigma_{\tau o} = \sigma_{lo}/c$, I_b – the average bunch current, Z_{eff} – the effective longitudinal broadband impedance, T_o and $\omega_o = \frac{2\pi}{T_o}$ – the period and the circular frequency of the revolutions, $\beta = {}^{v}/_{c}$ – the relativistic velocity factor.

The second equation in (3) is written based on the assumption that the energy spread is constant under the potential well distortion. However, the dependence of the energy spread on the number of particles is given at least by the IBS. Then the relation between the longitudinal size of the bunch and the energy spread has the form similar to formula (1), but ω_{so} is replaced by ω_s, and $\frac{\sigma_{E\gamma}}{E}$

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is replaced by the energy spread given by the IBS – $\frac{\sigma_E}{E}$. It is assumed here that the longitudinal particle distribution remains Gaussian in the bunch.

The microwave instability and the turbulent increase of the sizes and the energy spread arise when the bunch current exceeds the threshold value [7,8]:

$$I_{th} = 2\pi \frac{\eta E}{e\left|\frac{Z}{n}\right|}\left(\frac{\sigma_E}{E}\right)^2, \quad (4)$$

where $I_{th} = \frac{\sqrt{2\pi}R}{\sigma_l} I_b$ (for the Gaussian bunch), R – the average radius of the accelerator orbit, $\left|\frac{Z}{n}\right|$ – the effective longitudinal broadband impedance, that differ from Z_{eff}. The energy spread depends on the bunch current as the cube root above the threshold value.

THE TECHNICAL EQUIPMENT

The optical observation station was placed on one of the SR output channels of the SIBERIA-2. Calculated values of the beta-functions and the dispersion at the radiation point are: $\beta_x = 1.936$ m, $D_x = 0.377$ m, $\beta_y = 6.529$ m. The main equipment of the station for monitoring the parameters of electron bunches in real time and for measurements is an interferometer, a CCD camera and an optical dissector with electric focusing and deflection. Data obtained from the CCD camera for measuring the horizontal size and from the optical dissector for measuring the longitudinal size are approximated by the Gaussian function. The technical resolution for the CCD camera is 80 μm, for the optical dissector is 40 pc. The interferometer is used to measure the vertical size of the bunch. The technical resolution of the interferometer is 5 μm.

Observations of the beam current spectrum are carried out using the digital spectrum analyzer Rohde&Schwarz FSW, operating in the frequency range from 2 Hz to 13.6 GHz. The signal to the spectrum analyzer comes from the current sensor installed in the storage ring.

Measurements of the average value of the electron beam current are also carried out using a sensor located in the storage ring. The signal from the sensor is sent to the ADC, its statistical error is 3 μA. The zero value of the current sensor is taken into account for each series of measurements.

MEASUREMENTS

Two series of measurements are presented here. The measurements were carried out at different times. The main parameters of the storage ring corresponding to the measurements are presented in Table 1. The ratio of the vertical and horizontal emittances was determined from measurements of the betatron frequencies [9].

The measured dependences of the longitudinal size on the bunch current are shown in Fig. 1-2 (blue points) for the first and the second series of measurements, respectively. The theoretical curves were put on the experimental points: the current dependences given by the IBS and calculated in the ZAP (orange solid lines); the current dependences given by the potential well distortion effect at the constant energy spread (green solid lines); the current dependences given by the potential well distortion effect taking into account the current dependence of the energy spread due to the IBS (red solid lines). The values of the longitudinal size at the zero current (yellow solid lines) are also presented in Fig. 1-2.

Table 1: The Storage Ring Parameters

Parameters/№ of the Series	1st Series	2nd Series
Energy, MeV	445.15	445.26
RF voltage, kV	323	204
Frequency f_o, kHz	2414.993	2414.977
Frequency f_s, kHz	22.92	18.22
Emittance Ratio, %	3.846	1.354

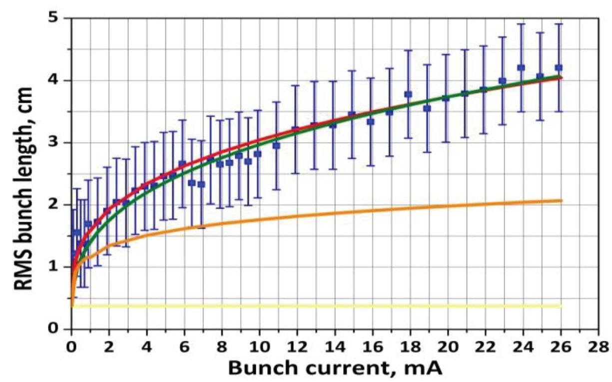

Figure 1: RMS bunch length vs. bunch current. The first series of measurements.

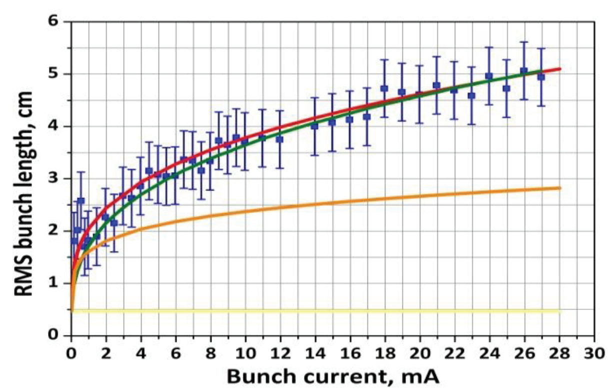

Figure 2: RMS bunch length vs. bunch current. The second series of measurements.

The measured current dependences of the horizontal size of the bunch are shown in Fig. 3-4 (blue points) for the first and the second series of measurements, respectively. The theoretical curves given by the IBS with (green solid lines) and without (red solid lines) taking into account the bunch lengthening due to the potential well distortion effect were put on experimental points. The values of the horizontal size at zero current (yellow solid lines) are also shown in Fig. 3-4.

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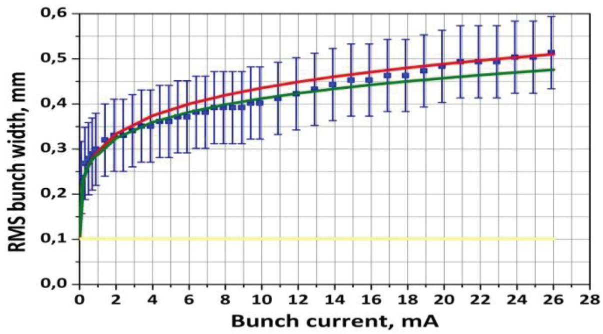

Figure 3: RMS bunch width vs. bunch current. The first series of measurements.

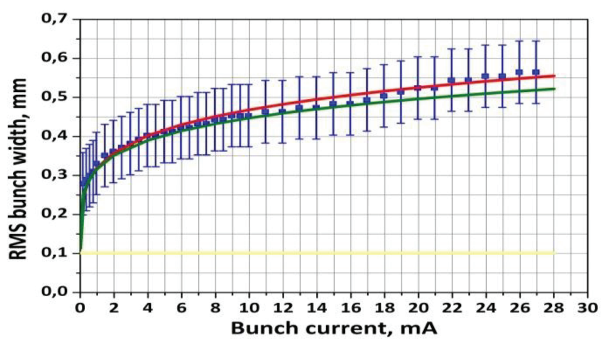

Figure 4: RMS bunch width vs. bunch current. The second series of measurements.

It is interesting to note according to the obtained results that the bunch sizes are determined mainly by the action of the IBS and the potential well distortion effect at the energy 450 MeV in the storage ring SIBERIA-2. The IBS determines the horizontal size and makes a significant contribution to the longitudinal size at low currents up to nearly 3 mA depending on the conditions. The lengthening due to the potential well distortion effect affects the values of the horizontal size with increasing number of particles in the bunch.

The additional growth of the horizontal size at the currents exceeding 10 mA was noted in the first series of measurements (Fig. 3), in the second series of measurements the additional growth was noted at the currents of more than 16 mA (Fig. 4). At present it is difficult to say with what the observed phenomenon is connected. In the first series a sextupole mode of coherent synchrotron oscillations with small amplitude appeared at 53.24 kHz in the beam current spectrum starting at 10 mA and higher (Fig. 5). In the second series the coherent components of the oscillations were not marked in the entire current range (Fig. 6). The question remains open whether the effect is the consequence of synchrotron coherent oscillations and/or betatron oscillations.

The longitudinal effective impedance of the vacuum chamber of the SIBERIA-2 obtained from the approximation of experimental points by the dependence that takes into account the growth of the energy spread due to the IBS is approximately 2.35 Ω under the conditions of the first series of measurements and 2.60 Ω under the conditions of the second series of measurements. By approximating the current dependence obtained from (3) at the constant energy spread, the effective impedance was approximately 3.23 Ω and 3.77 Ω, respectively. The difference in the values of the effective impedance of the two measurements is probably due to the peculiarity of the accelerating structure of the SIBERIA-2. The peculiarity is that the accelerating structure consists of three RF-cavities with the wide spectrum of HOMs (up to 2.3 GHz). Depending on the parameters of the operation, which affect the bunch length and consequently the spectrum of the beam current, the spectrum of HOMs interacting with the bunch can vary.

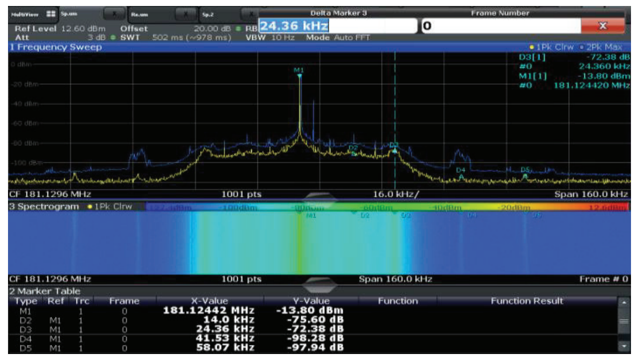

Figure 5: The narrow-band current spectrum at 15.3 mA. The first series of measurements.

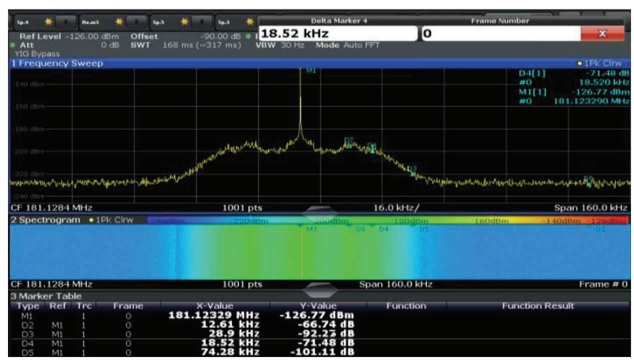

Figure 6: The narrow-band current spectrum at 11.9 mA. The second series of measurements.

CONCLUSION

The conducted studies showed that the bunch sizes are mainly determined by the potential well distortion effect and the multiple intra-beam scattering in the storage ring SIBERIA-2 operating in a single bunch mode at 450 MeV. The additional growth of the horizontal size above some electron currents remains a matter requiring further investigation. It is interesting to note that the microwave instability and turbulent increase of the bunch sizes were not observed under the experimental conditions.

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