BUNCH LENGTHENING STUDY IN BEPC

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Abstract

The bunch lengthening in the Beijing Electron - Positron Collider (BEPC) is investigated systematically with streak camera and the method of beam spectrum analysis. Many available results are obtained from the measurement and the corresponding scaling law is summarized in the light of the existing theoretical explanation. Due to its importance for BEPC upgrades, the related parameters and effects of bunch lengthening are studied in details.

I. INTRODUCTION

In electron - positron storage rings, bunch length and its lengthening are so important that people should cope with them much carefully as they will influence on the luminosity and machine performance directly. A high luminosity is the destination of every electron - positron collider, due to which, one can reduce the β functions at the interaction point while shortening the bunch length, especially for the lower RF frequency like 200 MHz in BEPC. Small coupling impedance is also considered attentively in the design of colliders in order to avoid bunch lengthening. In BEPC, an electron - positron collider running at the energy of 1.3∼2.8 GeV, bunch length is also significant to the machine performance and the luminosity upgrades, it is of course a probe of bunched beam instability. From the data of bunch length and its lengthening, we can fit them as a scaling law and deduce the beam current threshold, coupling impedance and some further understanding of the theories.

II. THEORETICAL ASPECTS

Some theories have been developed to explain the phenomena of bunch lengthening up to now. They are the potential well distortion model and the instability model. At very low currents the bunch length equals the natural bunch length σ_{l0}, which is determined by RF voltage, beam energy and other machine parameters.

The incoherent frequency shift and bunch length distortion (lengthening or shortening) will be caused by potential well effect with beam current. The incoherent tune shift is [1]

$$(\frac{\omega_s}{\omega_0}) = [1 - \Delta \sum_p j \frac{Z_{\|}(p)}{p} p^2 \sigma_0(p)] \tag{1}$$

where $Z_{\|}$ is the broad band impedance, Δ is a scaling factor as a function of RF voltage and beam current, $\sigma_0(p)$ is the amplitude of the stationary spectrum of Gaussian distribution at the frequency of $p\omega_0$. The energy spread is not affected by the potential well distortion in electron machines. So $\sigma_l/\sigma_{l0} = \omega_{s0}/\,\omega_s$ and for a long bunch ($\sigma_l > b$)

$$(\frac{\sigma_{l0}}{\sigma_l})^2 = 1 + \delta \frac{b^3}{\sigma_l^3} \tag{2}$$

where b is the radius of vacuum pipe and δ is proportional to Δ. One can see that the distortion (lengthening or shortening) of bunch length depends on δ, i.e. the impedance and the momentum compaction factor.

Due to the microwave instability, bunch lengthening happens on energy spread increasing when beam current is above the threshold. According to Boussard [2], the bunch lengthens with the following relation:

$$\sigma_l = (\frac{\sqrt{2\pi} e R^3 I_b \alpha_p}{F E \nu_s^2} |\frac{Z_{\|}}{n}|_0)^{1/3} \tag{3}$$

where I_b is the bunch current, α_p the momentum compaction factor, R the radius of collider, e the charge of electron, E the beam energy, ν_s the synchrotron tune, F the distribution factor and $|\frac{Z_{\|}}{n}|_0$ the longitudinal coupling impedance at lower frequency. From this formula, one can see that the bunch length is proportional to the cubic root of a scaling parameter ξ, which is defined as $\xi = I_b \alpha_p / E \nu_s^2$. It can be written as

$$\sigma_l \propto (\xi |\frac{Z_{\|}}{n}|_0)^{1/3} \tag{4}$$

One can calculate the particle longitudinal distortion in phase space with and without potential well distortion and microwave instability then compare it with the measurement. It is expected to better understand the mechanism of bunch lengthening and energy spread widening.

In reference [3], a scaling law for SPEAR had been concluded. It predicts the bunch length σ_l depends on the parameter ξ as

$$\sigma_l \propto (\xi Z_0 R^3)^{\frac{1}{2+a}} \tag{5}$$

$$Z(\omega) = 2\pi R Z_0 \omega^a . \tag{6}$$

Here, Z_0 is the impedance parameter and (6) assumes a power law behaviour of the coupling impedance responsible for the instability.

In the real case, the behaviour of bunch lengthening over the whole beam current range is as a synthesis affected by the potential well distortion and the microwave instability.

III. INSTRUMENTATION AND DATA ACQUISITION

Two ways of bunch length measurement have been adopted in the BEPC: streak camera and beam spectrum analysis. With the streak camera, the longitudinal particle distribution is gained by looking at the light of synchrotron radiation from a bending magnet. The light pulse is picked up by the streak camera with a time resolution of a few picoseconds at the end of the synchrotron radiation beam line. The cable used in the instrument was calibrated before measurements. The overall measurement error of this set of apparatus is less than 20 % [4].

Another way to measure the bunch length in BEPC is the beam spectrum analysis. In this method [5], a technique of measuring bunch length by the comparison of two Fourier components of the beam has been applied to an electron bunch. A monitor for real time measurement of the bunch length has been set up with a stripline electrode of 277 mm in length. Assuming a Gaussian longitudinal distribution of rms bunch length σ_l, the Fourier component of the n-th harmonic is given by

$$V(n\omega_0) = 2V_0 exp[-n^2\omega_0^2\sigma_l^2/2] \tag{7}$$

Here n is an integer, ω_0 the revolution frequency, $V(n\omega_0)$ the induced voltage on an ideal beam pickup and V_0 the DC component. The rms bunch length is obtained from the ratio between two Fourier components as

$$\sigma_l = \frac{1}{\omega_0}\sqrt{\frac{2}{(n_2^2 - n_1^2)} \cdot \ln\frac{V_1(n_1\omega_0)}{V_2(n_2\omega_0)}} \tag{8}$$

where V_1 and V_2 are Fourier components at n_1-th and n_2-th harmonics of the revolution frequency and $n_2 > n_1$. The measurement of bunch length by this way has an accuracy of 10 % relatively with a dynamic range of 25dB - 35dB.

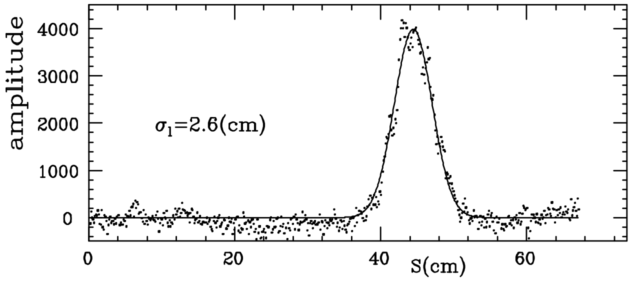

Fig. 1 Longitudinal Distribution at Low Current

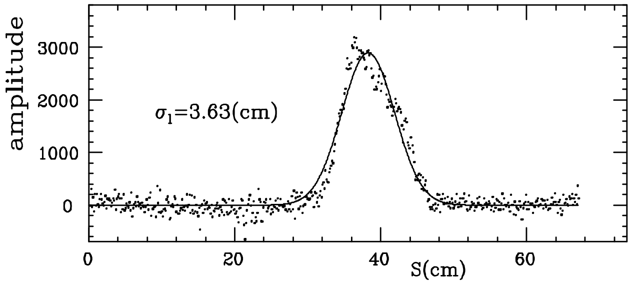

Fig. 2 Longitudinal Distribution at High Current

IV. EXPERIMENTAL RESULTS

A. Data analysis

More than 250 effective experimental points were obtained with various beam energies, RF voltages and beam currents. Fig. 1 and Fig. 2 display the longitudinal distribution of bunches measured with the streak camera at low and high intensity respectively. Fig. 3 and Fig. 4 show some prototype data of bunch length changing with beam current under different RF voltages. Fig. 5 and Fig. 6 give the variation of the bunch length versus current at different energy and momentum compaction factor. In these figures, one can see that RF voltage determines the bunch length and its lengthening as the beam currents increase. In different energy E and momentum compaction factor α_p, bunch length varies in the same way, i.e., E and α_p do not change the bunch lengthening principle. This is because that the longitudinal tune dependence on the beam current is very weak in the BEPC operation region [6].

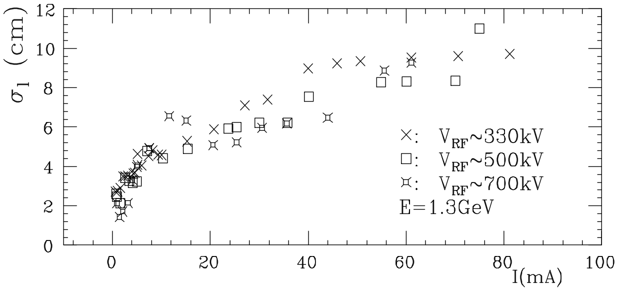

Fig. 3 Bunch Length vs. Beam Current

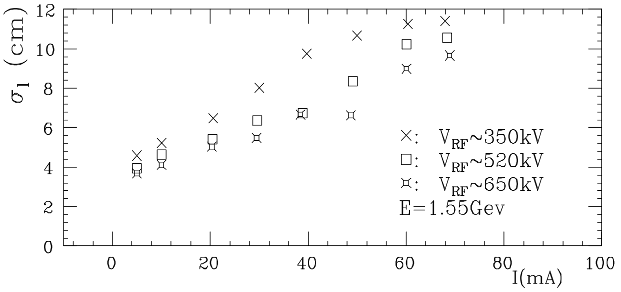

Fig. 4 Bunch Length vs. Beam Current

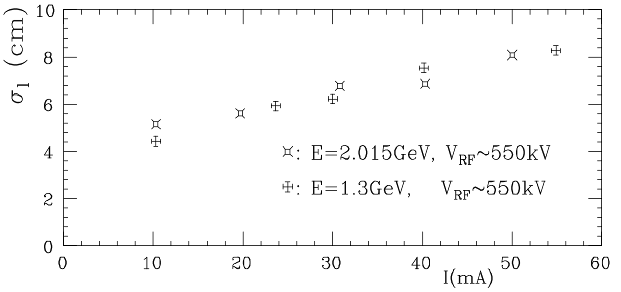

Fig. 5 Bunch Length vs. Beam Current

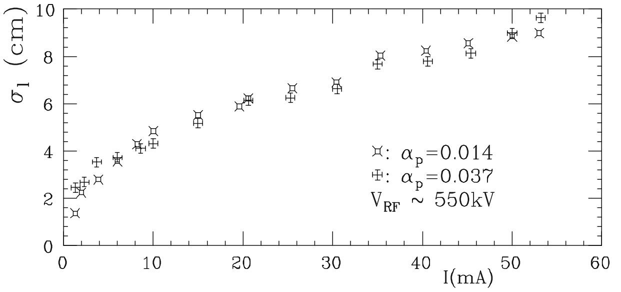

Fig. 6 Bunch Length vs. Beam Current

The variation of energy spread with beam current increase at different RF voltages and different energies are given in Fig. 7.

It seems that the energy spread is almost independent on RF voltage and that the threshold of the microwave instability is around 6 mA at 1.3 GeV and 15 mA at 2.015 GeV.

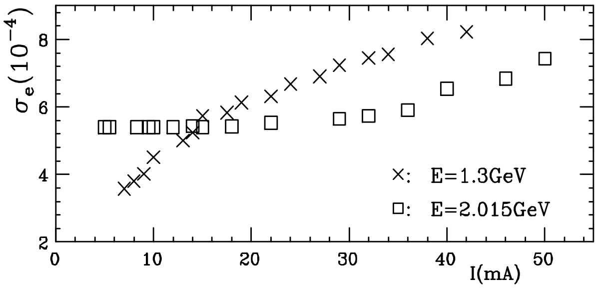

Fig. 7 Energy Spread vs. Beam Current

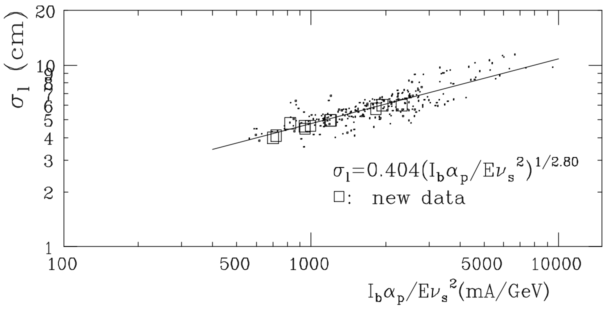

Fig. 8 Bunch Length vs. Scaling Parameter

According to the simulation study, the bunch shape should deviate from Gaussian distribution by the potential well effect. However, it can not be distinguished clearly in our observation. The reason might be this effect is too weak in BEPC and it was covered within the measurement error.

B. The scaling law

When fitting all bunch length data to calculate the scaling parameter ξ and plotting them as σ_l versus ξ in Fig. 8, the frequency dependent factor can be determined as a=0.80 for the long bunch. The scaling law of BEPC is given as

$$\sigma_l(cm) = 0.404 \times (\frac{I_b(mA)\alpha_p}{E(GeV)\nu_s^2})^{1/2.80} \qquad (9)$$

which looks like agreeable with the theoretical prediction of eq.(3). Some new measurement points measured at higher RF voltage fit the scaling law fairly well. However, the bunch lengths of the recent measurement are somewhat shorter than that predicted by the scaling law. This might be due to removing two extra kickers from the ring for reducing the impedance last summer.

To all measured data, we calculated their rms error as follows:

$$\delta(rms) = \sqrt{\frac{\sum(\frac{\sigma_c-\sigma_i}{\sigma_c})^2}{N}} \qquad (10)$$

Here, σ_c is the value calculated from eq.(10), σ_i the measured value and N the number of measured points. Being compared with the method of beam spectrum, whose rms error is 16.1 %, the rms error from the streak camera is 12.5 %, and the total rms error is 17.5 %. It stands for the deviation between the measured points and fitting points. The errors include not only systematic and random errors, but also the fluctuation of bunch length due to longitudinal dipole and quadrupole oscillation.

The measurement result shows that the bunch length is 4.0 cm at 2.015 GeV, 35 mA and 2.0 MV of RF voltage. From eq.(10), we also deduce that bunch length is about 4.5 cm at 2.015 GeV, 50 mA and 2.4 MV of RF voltage. The BEPC luminosity upgrades, especially the success of mini-β scheme, are mainly constrained by the bunch length.

C. Threshold current and impedance

Using eq.(10) and equating σ_l to the natural unperturbed bunch length σ_{l0}, current threshold can be predicted as

$$I_{th} = 13.18\alpha_p^{1.80}E^{3.80}\nu_s^{-0.80} \qquad (11)$$

Furthermore, from eq.(10) we can get the value of the impedance driving the potential well distortion and the microwave instability to $|\frac{Z_\parallel}{n}|_0$=3.54$\Omega$. It is in good agreement with the impedance measured with other methods.

V. CONCLUSION

Bunch length and its lengthening are very important, especially for the BEPC luminosity upgrades. From the bunch length measurement, we get a scaling law of BEPC and then estimated the coupling impedance. Different beam energy and α_p do not affect the bunch length. The mechanism of the bunch lengthening in BEPC could be clarified by comparing the measurement results to the analytical calculation in the longitudinal phase space with the improved measurement accuracy.

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References

[1] Q. Qin et al., Proc. of the International Workshop on Particle Dynamics in Accelerator, Tsukuba, Japan, 1994.

[2] D. Boussard, CERN LABII/RF/Int./75-2, 1975.

[3] A. W. Chao and J. Gareyte, PEP Note 224, 1976.

[4] W. Liu, Bunch Length Measurement with a Picosecond Streak Camera in the BEPC, Internal report, 1993.

[5] T. Ieiri, Proc. of the Workshop on Advanced Beam Instrumentation, 1991.

[6] Z. Guo et al., Proc. of IEEE PAC93, 1993.