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BUNCH LENGTH MEASUREMENT AND ITS LENGTHENING IN HLS*

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Abstract

The paper discusses the method and principle of bunch length measured by HP54121T 20GHz digital sampling oscilloscope in Hefei Light Source (HLS) ring. The measurement results of the bunch length and the energy spread are given. The rms. bunch length is about 3.8 ~ 10.33cm. A new theory on the bunch lengthening is used to explain the experimental results. It is proved that the beam-cavity interaction is the most important factor to the multi-bunch lengthening of HLS.

1 INTRODUCTION

As bunch length and its lengthening have an influence on the machine performance in an electron storage ring, these measurements are very important. Several methods to measure the bunch lengths have been developed, for example, electronic measurement, optical measurement and optoelectronic measurement. We use a 20 GHz digital sampling oscilloscope to measure the bunch length and its lengthening. In this method, a bandwidth stripline electrode with a length of L=30cm and an impedance of Z_0=50 Ω is used for picking up beam signal.

There are two sorts of theories to explain the bunch lengthening and the energy spread widening, i.e. the potential well distortion and microwave instability. But, the existing theories are difficult to explain the experimental results. In the reference[1], the distribution function of the particles is gained with the statistical mechanics method for intense current. The theory unites the existing potential well distortion and microwave instability. The theory proves that the bunch lengthening is a multi-bunch effect in nature. So the theory points out the importance of the narrow-band impedance to the bunch lengthening.

2 MEASUREMENT PRINCIPLE

2.1 Stripline monitor

The stripline is an electrode with the characteristic impedance Z_0, usually longer than the characteristic bunch length. By a suitable choice of the ratio between the stripline width and distance from the vacuum pipe, the characteristic impedance is made 50Ω. The electrode is terminated at both ends via coaxial vacuum feedthrough into termination loads matched to Z_0 .

In principle we get a useful signal only at the up-stream terminal of the monitor. The voltage signal at the up-stream load resistor is a doublet of opposing polarity reproducing the longitudinal time distribution of the beam current and separated in time by an interval Δt=2L/c, where L is the stripline length. So, the time domain voltage signal of the matched stripline at the up-stream terminal for a centred beam [2] is

$$v(t) \approx \frac{Z_0}{2}\left(\frac{\alpha}{2\pi}\right)\left[i_b(t) - i_b\left(t - \frac{2L}{c}\right)\right] \qquad (1)$$

Where, α is the opening angle of the stripline, $i_b(t)$ is the instantaneous beam current, L =30 cm.

The voltage signal of stripline at the up-stream pot on HP54121T 20GHz digital sampling oscilloscope is shown Fig.1. Here, the negative pulse is signal sensed on stripline by the beam i_b (t). Therefore, the pulse width of the beam signal may be measured by the voltage signal of the stipline.

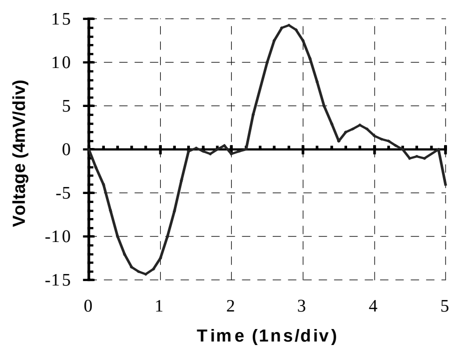

Figure 1: The voltage signal of the stripline on HP54121T

2.2 The relation between the bunch length and the FWHM of the time domain beam signal

We can assume that the bunch has a Gaussian longitudinal distribution in a ring. So, the beam current $i_b(t)$ can be expressed in the time domain as

$$i_b(t) = I_p \exp\left(-\frac{c^2 t^2}{2\sigma_s^2}\right) \qquad (2)$$

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Here, σ_s is the bunch length, I_p is the peak current of a bunch.

Because the pulse width of the beam signal can be expressed as the FWHM, we get

$$\sigma_s = c \times FWHM/2.3548 \qquad (3)$$

Therefore, the bunch length is got by measuring the FWHM of the beam signal.

3 THE SYSTEM COMBINATION

This bunch length measurement system consists of a stripline monitor, an attenuator, a 20GHz digital sampling oscilloscope HP54121T (Four Channel Test Set HP54121A and Mainframe HP54120B), a RF trigger system and a printer HP2225AB. A block diagram of this system is shown in Fig.2.

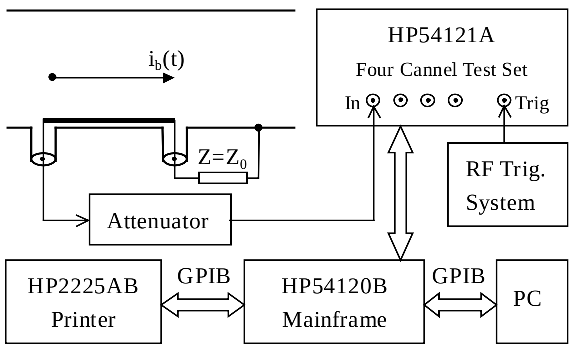

Figure 2: A block diagram of the bunch length measurement system

4 BUNCH LENGTHENING AND ENERGY SPREAD WIDENING

4.1 The measured result of the bunch lengthening and energy spread widening

We measure the FWHM of the beam signal with the bunch length measurement system in various beam currents[3]. The rms. bunch length is about 3.8 ~ 10.33 cm. The measured results are shown in Fig.3. I is the total current of forty five bunches.

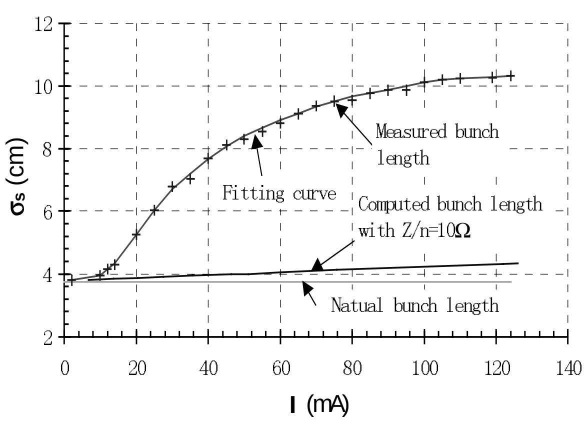

Figure 3: Bunch length vs. beam current

The energy spread is measured by decreasing the longitudinal acceptance via lowering the RF voltage until the longitudinal quantum lifetime becomes dominant. Then we can get the energy spread from measured quantum lifetime and the height of the RF bucket. The measured results are shown in Fig. 4

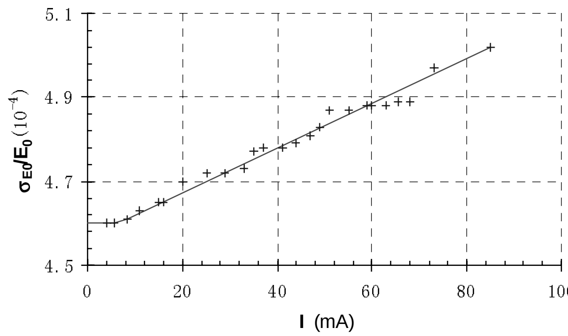

Figure 4: Energy spread vs. beam current

4.2 The new theory on bunch lengthening

The change of the particle energy in the interaction between the beam and the environment is written by[1]

$$U_W(\tau,\varepsilon) = -U_{W0} + B\tau + 2T_0\alpha_s\varepsilon \qquad (4)$$

Where, U_{w0}, B, α_s are independent of τ and ε. α_s is the growth rate of longitudinal instability generated by the interaction of the beam and the environment.

So, the bunch lengthening and the energy spread widening have given by

$$\sigma_E = \sqrt{Q/4\alpha_r'}, \quad \frac{\sigma_E}{\sigma_{E0}} = \sqrt{\frac{\alpha_r}{\alpha_r'}} \qquad (5)$$

Here, $Q = \dfrac{55hr_e m_0 c^4\gamma^7}{48\pi\sqrt{3}R^3}$, $\alpha_r' = \alpha_r - \alpha_s$

$$\frac{\sigma_s}{\sigma_{s0}} = \frac{\sigma_E}{\sigma_{E0}}\left(\frac{2\pi he\hat{V}_{rf}\left|\cos\varphi_s\right|}{2\pi he\hat{V}_{rf}\left|\cos\varphi_s'\right| + BT_0}\right)^{\frac{1}{2}} \qquad (6)$$

Where, α_r is the factor of damping, φ_s is the synchronous phase at zero current, φ_s' is the new synchronous phase under the interaction of the beam and the environment, h is the harmonic number, σ_{so} is the natural bunch length, σ_{Eo} is the natural energy spread. In HLS, $\sigma_{so} = 3.76cm$, $\sigma_{E0}/E_0 = 4.6\times10^{-4}$

For the inductive wall model, U_{w0}, B_{in} and α_s in Eq. (4) respectively are

$$U_{W0} = 0, \quad B_{in} = -\frac{\sqrt{2\pi}eR^2cI_b}{\sigma_s}\left|\frac{Z_{11}}{n}\right|_0, \quad \alpha_s = o$$

Where, R is the average radius of the machine, $|Z_{11}/n|_0$, the longitudinal impedance of the machine.

So, the effect of the inductive wall only generates the bunch lengthening, while the energy spread does not vary. The bunch lengthening is given by the following equation

$$\left(\frac{\sigma_s}{\sigma_{s0}}\right)^3-\left(\frac{\sigma_s}{\sigma_{s0}}\right)-\frac{\sqrt{2\pi}I_b\left|\frac{Z_{11}}{n}\right|_0}{h\hat{V}_{rf}\left|\cos\varphi_s\right|}\left(\frac{R}{\sigma_{s0}}\right)^3=0 \qquad (7)$$

For the microwave instability model, $\alpha_s\neq 0$. So, the bunch lengthening and the energy spread widening are

$$\left(\frac{\sigma_E}{E_0}\right)^2=\frac{eI_b}{\sqrt{2\pi}E_0\alpha_p}\left(\frac{R}{\sigma_s}\right)\left|\frac{Z_{11}}{n}\right|_{crit},\quad \frac{\sigma_s}{\sigma_{so}}=\frac{\sigma_E}{\sigma_{E0}} \qquad (8)$$

Where, $|Z_{11}/n|_{crit}$ is the impedance at the threshold of the microwave instability.

If the inductive wall model and the microwave instability are regarded together, the bunch lengthening is given by the following equation

$$\left(\frac{\sigma_s}{R}\right)^3=\frac{\sqrt{2\pi}I_b}{h\hat{V}_{rf}\left|\cos\varphi_s\right|}\left(\left|\frac{Z_{11}}{n}\right|_0+\left|\frac{Z_{11}}{n}\right|_{crit}\right) \qquad (9)$$

At the threshold of the microwave instability, the bunch length given the Eq. (7) should be equal to the bunch length by the Eq. (9). Then

$$\frac{\sigma_{sth}}{\sigma_{s0}}=\left(1+\frac{\left|\frac{Z_{11}}{n}\right|_0}{\left|\frac{Z_{11}}{n}\right|_{crit}}\right)^{1/2} \qquad (10)$$

For long bunch, we will assume that the frequency of the microwave instability is lower than the cut-off frequency. So, $|Z_{11}/n|_{crit}=|Z_{11}/n|_0$. Then,

$$\sigma_{sth}=\sqrt{2}\sigma_{s0} \qquad (11)$$

$$I_{bth}=\left(\frac{\sigma_{s0}}{R}\right)^3\frac{h\hat{V}_{rf}\left|\cos\varphi_s\right|}{\sqrt{\pi}\left|\frac{Z_{11}}{n}\right|_0}=\frac{2\sqrt{\pi}\alpha_pE_0}{e\left|\frac{Z_{11}}{n}\right|_0}\left(\frac{\sigma_{s0}}{R}\right)\left(\frac{\sigma_{\varepsilon 0}}{E_0}\right)^2 \qquad (12)$$

Where, α_p is the momentum compact factor.

According to the parameter of the machine, we get

$$I_{bth}\left|\frac{Z_{11}}{n}\right|_0=103.1mV$$

If it is considered that $|Z_{11}/n|_0=10\Omega$, then I_{bth}=10.3mA. That is, the total current is 463.5mA.

Substituting Eq. (12) it into Eq. (7), we get

$$\left(\frac{\sigma_s}{\sigma_{s0}}\right)^3-\left(\frac{\sigma_s}{\sigma_{s0}}\right)-\sqrt{2}\frac{I_b}{I_{bth}}=0 \qquad (13)$$

According to Eq. (13), the curve of the bunch lengthening computed by the inductive wall model is shown in Fig.3. So, the microwave instability does not occur in our experiment.

Now, we analyse that the narrow band impedance acts up on the bunch lengthening. When a narrow band impedance $Z(\omega)$ acts up on the beam, U_{w0}, B_c and α_s in Eq. (4) respectively are

$$U_{w0}=2eI\sum_{K=1}^{\infty}e^{-K^2M^2\omega_0^2\sigma_s/2c^2}Z_R(KM\omega_0) \qquad (13)$$

$$\begin{aligned}B_c=eI\omega_0\sum_{K=1}^{\infty}&e^{-(KM+\mu)^2\omega_0^2\sigma_s/2c^2}[(KM+\mu)Z_i^+\\&+e^{-(KM-\mu)^2\omega_0^2\sigma_s/2c^2}(KM-\mu)Z_i^-\\&-2e^{-K^2M^2\omega_0^2\sigma_s/2c^2}KMZ_i\,]\end{aligned} \qquad (14)$$

$$\begin{aligned}\alpha_s=\frac{\alpha_p eT\omega_0}{4\pi\nu_sE_0}\sum_{K=1}^{\infty}&e^{-(KM+\mu)^2\omega_0^2\sigma_s/2c^2}[(KM+\mu)Z_R^+\\&+e^{-(KM-\mu)^2\omega_0^2\sigma_s/2c^2}(KM-\mu)Z_R^-]\end{aligned} \qquad (15)$$

Where, U_{w0} indicates the change of synchronous phase generated by $Z(\omega)$ so as to generate the bunch lengthening; B_c indicates the RF potential well distortion generated by $Z(\omega)$ so as to generate the bunch lengthening; α_s is the growth rate of longitudinal instability generated by $Z(\omega)$ so as to generated the energy spread widening.

The experiments have shown that the longitudinal instability occurs at a low current threshold of 10mA(total current) in HLS[4]. Therefore, the beam-cavity interaction is the most important factor to the bunch lengthening of HLS.

5 CONCLUSION

According to the experimental results of the bunch lengthening and the energy spread widening in HLS, the conclusions are got as follows:

(1). When the total current is lower than 10mA, the bunch lengthening is generated by the inductive wall, while the energy spread basically maintained constant,.

(2). When the total current is greater than 10mA, which is the threshold current of the longitudinal instability, it is obvious that the bunch lengthening and the energy spread widening. So, above 10mA, except that the bunch lengthening is generated by the inductive wall, the bunch lengthening and the energy spread widening are mainly generated by the narrow band impedance.

On the base of the new theory, the experimental results of the bunch lengthening are explained reasonably.

6 REFERENCES

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