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Transverse single bunch instability study on BEPC ☆

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Abstract

In recent years, a lot of experiments were done on ESRF and ELETTRA to study the single bunch transverse instability. To prevent such instabilities on BEPCII in the future, experiments were made on the single bunch transverse instability threshold current versus the chromaticity on BEPC. By analyzing the experimental data based on the theory developed in [J. Gao, Nucl. Instr. and Meth. A 416 (1998) 186 (see also PAC97, Vancouver, Canada, 1997, p. 1605).], the transverse loss factor of BEPC and the corresponding scaling law are obtained.

Keywords: Single bunch transverse instability; Chromaticity; BEPC; Transverse loss factor

1. Introduction

In recent years, a lot of experiments were done on ESRF and ELETTRA to study the single bunch transverse instability [1–5].

Single bunch transverse instabilities in electron storage rings behave differently with respect to different values of chromaticity, ξ_c [6,7]. When the chromaticity is negative it is known that the bunch is transversely unstable due to a mechanism called head–tail instability. At $\xi_c = 0$ the collective motion of the particles inside a bunch can benefit only little from residual Landau damping due to an equivalent *residual chromaticity*, ξ_{c0}, which is defined as: $\xi_{c0} = (1/2\pi\beta_n)\eta L$, where η is the momentum compaction factor, L is the machine circumference, and the averaged value of beta function β_n is defined as $1/\beta_n = (1/L)\int_0^L(\mathrm{d}s/\beta(s))$. The reader should not confuse the notation ξ_{c0} with *natural chromaticity*, since its real physical cause is η. By a rough estimate, one finds that $\xi_{c0} \approx v\eta$, where v is the tune shift of the machine. In fact, all the existing electron storage rings have their chromaticities compensated above zero (even if very near zero sometimes). When $\xi_c > 0$, the bunch will be not only free from the head–tail instability, but also its transverse collective motion can be guaranteed by sufficient Landau damping. The instability will occur only when Landau damping effect is destroyed at a specific bunch current threshold, I_{th}. The behavior is theoretically explained in detail in Ref. [8] (where $\xi_{c0,y}$ has been neglected). In recent years, a lot of experiments were done on ESRF and ELETTRA to study the single bunch transverse instability [1–5]. Experiments indicate a strong nonlinear dependence of I_{th} with respect to ξ_c. The aim of this paper is to study this nonlinear dependence and to determine the transverse loss factor of BEPC through experiments by applying the theory developed in Ref. [8]. BEPC has a 4-fold symmetrical structure, consisting of the IR/RF, the arc and the injection regions. The main parameters of the experimental mode of BEPC are shown in Table 1.

In the following sections, the basic theory of this experiment, the experiment itself, the data analysis, and the conclusion will be presented.

2. Review of theory

For a given vertical chromaticity $\xi_{c,y}$ (we will limit to our discussion on the vertical plane where the instability starts first due to stronger wake field), the threshold current for

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Table 1
Main parameters of BEPC

E	1.3 GeV	σ_{z0}	1.88–1.33 cm
C	240.4 m	f_{rf}	199 MHz
V_{rf}	0.4–0.8 MV	α_p	0.016
$I_{b,\max}$	137 mA	v_x/v_y	8.72/4.75
$N_{\mathrm{sextupole}}$	36	σ_e	3.432×10^{-4}

the elimination of Landau damping is expressed as [8]

$$I_{\mathrm{th}}=\frac{4f_y\sigma_{\varepsilon0}\mathbf{R}_\varepsilon(I_{\mathrm{th}})|\xi^*_{\mathrm{c},y}|}{e\langle\beta_{y,c}\rangle K_\perp^{\mathrm{tot}}(\sigma_z(I_{\mathrm{th}}))},\tag{1}$$

where f_y is the vertical betatron frequency, $\sigma_{\varepsilon0}$ is the natural energy spread. $\xi^*_{\mathrm{c},y}=\xi_{\mathrm{c},y}+\xi_{\mathrm{c0},y}$, $\xi_{\mathrm{c0},y}$ is the residual chromaticity in vertical plane defined above; $\mathbf{R}_\varepsilon(I)=\sigma_\varepsilon(I)/\sigma_{\varepsilon0}$, e is the electric charge of electron. $K_\perp^{\mathrm{tot}}(\sigma_z(I))$ is the total transverse loss factor (vertical plane) of the machine, $\langle\beta_{y,c}\rangle$ is the vertical beta function in the RF cavity regime where the main contribution to $K_\perp^{\mathrm{tot}}(\sigma_z(I))$ is believed to be, and $\sigma_z(I)$ is the current dependent bunch length. Defining $\mathbf{R}_z(I)=\sigma_z(I)/\sigma_{z0}$, one has $K_\perp^{\mathrm{tot}}(\sigma_z(I))=K_\perp^{\mathrm{tot}}(\sigma_{z0})/\mathbf{R}_z^{\Theta}(I)$, where Θ is a constant for a given machine. We distinguish two different regimes. The first regime corresponds to very small values of $\xi_{\mathrm{c},y}$. In this case I_{th} is located in the potential well distortion dominated bunch lengthening region, and one has $\mathbf{R}_\varepsilon\approx1$. The second regime applies to large $\xi_{\mathrm{c},y}$. I_{th} is located in the microwave instability dominated bunch lengthening region with $\mathbf{R}_\varepsilon\approx\mathbf{R}_z$ [9]. Taking $\mathbf{R}_z(I)\approx CI^{1/3}$ as a rough global scaling law where C is a constant, for these two regimes Eq. (1) becomes

$$I_{\mathrm{th}}=\left(\frac{4f_y\sigma_{\varepsilon0}C^{\Theta}|\xi^*_{\mathrm{c},y}|}{e\langle\beta_{y,c}\rangle K_\perp^{\mathrm{tot}}(\sigma_{z0})}\right)^{3/(3-\Theta)}\tag{2}$$

and

$$I_{\mathrm{th}}=\left(\frac{4f_y\sigma_{\varepsilon0}C^{\Theta+1}|\xi^*_{\mathrm{c},y}|}{e\langle\beta_{y,c}\rangle K_\perp^{\mathrm{tot}}(\sigma_{z0})}\right)^{3/(2-\Theta)}.\tag{3}$$

3. Transverse instability experiment

3.1. Experimental process and the results

The BEPC machine mode was set as the synchrotron radiation's injection mode. The beam energy was 1.3 GeV. The beam lifetime was around 10 h.

The voltage of the RF cavity was set as 300, 400, 600, 800 kV, respectively. The chromaticity was increased from 0 to 4 with the step size 1. Then one single bunch was injected into the ring until it came to the saturation current. During this process, the single bunch threshold current and the mode coupling were measured. The conclusion was that: the beam could be injected into the ring when the vertical chromaticity was between 0 and 4; the single bunch threshold current increased at first and then decreased; the single bunch threshold current had its maximum value when the chromaticity was 1.2 approximately.

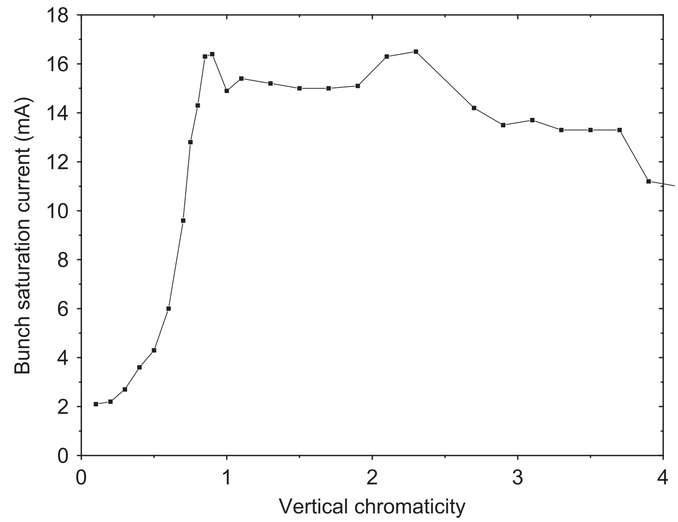

Fig. 1.

Next, the step size of the chromaticity variation was set more meticulously as 0.1 when the chromaticity was increased from 0 to 4. During this process, the single bunch threshold current and the tunes of the two modes were measured. The conclusion was that: when the chromaticity was between 0 and 1, the threshold current was a power function of the vertical chromaticity; when the chromaticity was between 1 and 4, the threshold current decreased with the vertical chromaticity; for each value of the chromaticity, the bunch current at which the transverse mode coupling instability appeared was reproducible. The results were shown in Fig. 1. When the chromaticity is smaller than 1, the beam lifetime is longer than 15 h and we can see the transverse mode coupling signal on the tune monitor.

It could be seen that the experimental result was abnormal when the vertical chromaticity was above 1 approximately. That was because the on-line chromaticity correction program only changed eight of the total 16 sextupoles' strength when it did the chromaticity correction, therefore the dynamic aperture was very small due to the strong sextupole strength and the beam lifetime decreased to less than 1 h accordingly.

3.2. The scaling law

From SPEAR scaling [10], one knows that the longitudinal loss factor of a storage ring scales with bunch length as $\sigma_z^{-1.21}$. As for the corresponding scaling law for the transverse loss factor, one can resort to the Panofsky–Wenzel theorem [11]. Using the SPEAR impedance-frequency dependence function and applying the Panofksy–Wenzel theorem, one can prove that $\Theta=0.7$. The machine study of Super-ACO [12] shows numerically that $\Theta=0.7$. Taking $\Theta=0.7$ as a universal scaling law for transverse