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EXPERIMENTAL INVESTIGATION OF BEAM INSTABILITY IN BEPCII*

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Abstract

With the physical operations of the Upgraded Beijing Electron-Positron Collider (BEPCII), thresholds on collision luminosity and beam current have been presented due to various factors such as collision background, noise, and equipment stability and so on. One of the most serious influences on beam dynamics was beam instability which has been exhibited. The comprehensive experimental investigation on beam instabilities in BEPCII is necessary on beam dynamics but also referential to future machine upgrade. Over the past two years, the experimental investigation on beam instability has been carried on, which are source from the various couple impedances, including broadband and narrowband impedances. The measured impedance values are compared with its design.

INTRODUCTION

BEPCII, the Upgraded project of Beijing Electron-Positron Collider, is the only machine operating in τ-charm energy range of 1.0 to 2.1 GeV, and peak luminosity of 1.0×10^{33} cm^{-2}s^{-1} at the optimized beam energy of 1.89 GeV [1]. The peak luminosity, 1.096×10^{33} cm^{-2}s^{-1}, was achieved during the physical run in January 2023. Under such high beam current, 849 mA × 852 mA, the serious beam instabilities have been displayed, such as bunch lengthening, coupled-bunch instability and so on, which lead to the beam quality deterioration, luminosity decline, and threshold of the beam current. These instabilities may be critical bottleneck for pushing the beam current and collision luminosity to higher level. A comprehensive investigation on instabilities in BEPCII is critical for high luminosity stable operation. The main parameters of BEPCII rings are listed in Table 1 [2]. The BPR and BER mean for the Positron Ring and Electron Ring of BEPCII, respectively.

Table 1: Main Parameters of BEPCII

Parameters	BPR	BER
Circumference (m)	237.53	
Beam energy (GeV)	1.89	
RF frequency (MHz)	499.8	
Harmonic number	396	
Bunch number	118	
Horizontal tune	7.505/5.568	7.506/5.572
Synchrotron tune	0.0299	0.0296
Pipe radius (mm)	54/26	

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BUNCH LENGTHENING & BROADBAND IMPEDANCE

The longitudinal microwave instability, caused by the longitudinal broadband impedance, can induce bunch lengthening. The classical formula for bunch lengthening would be written as [3],

$$\left(\frac{\sigma_l}{\sigma_{l0}}\right)^3 - \left(\frac{\sigma_l}{\sigma_{l0}}\right) + I_b \frac{\alpha_p Im\left(\frac{Z^{\parallel}}{n}\right)_{eff}}{\sqrt{2\pi}\nu_{s0}^2 (E_0/e)} \left(\frac{R}{\sigma_{l0}}\right)^3 = 0, \quad (1)$$

where $Im\left(\frac{Z^{\parallel}}{n}\right)_{eff}$ is the longitudinal broadband impedance, I_b is the bunch current, E_0 is the beam energy, α_p is the momentum compaction factor, ν_{s0} is the synchrotron oscillation tune, R is the ring radius, and σ_{l0} is the natural bunch length. In the experimental measurements, a streak camera was used to measure the bunch lengths of single bunch in BPR and BER with bunch current ranging from 1.0 mA to 19.0 mA, as shown in Fig. 1. Fitting the experimental data of bunch lengths at different currents for the impedance values and bunch natural length of BPR and BER can be obtained as, 0.176 Ω, 0.153 Ω, 13.05mm and 12.91mm, respectively. The longitudinal broadband impedance of BPR is slightly greater than that of BER, and both of them are below the design impedance value of 0.27 Ω for BEPCII [2].

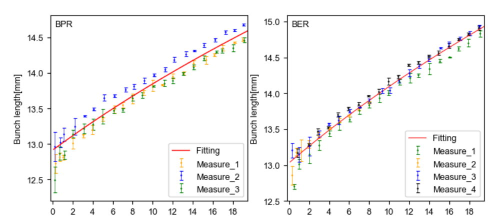

Figure 1: Bunch length vs current.

TRANSVERSE MODE COUPLING INSTABILITY & BROADBAND IMPEDANCE

The transverse mode coupling instability, caused by the transverse broadband impedance, can induce the tune shift of modes. The relationship between the betatron tune shift and bunch current can be written as [4]

$$\frac{d\nu_\beta}{dI} = \frac{1}{4\sqrt{\pi}} \frac{c^2}{(E_0/e)\nu_\beta \omega_0^2 \sigma_l} i(Z_1^{\perp})_{eff}, \quad (2)$$

where ν_β is the transverse betatron tune, I is the bunch current, c is the light speed, $(Z_1^{\perp})_{eff}$ is the transverse broadband impedance, E_0 is the beam energy, ω_0 is the revolution frequency, and σ_l is the bunch length.

During the experiments, single bunch oscillations were excited by injection kicker and feedback kicker separately,

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and the betatron tunes were obtained with FFT analysis at different currents, as shown in Fig. 2. By fitting the experimental results with Eq. (2), the transverse broad impedances of BPR and BER are obtained, which were listed in Table 2.

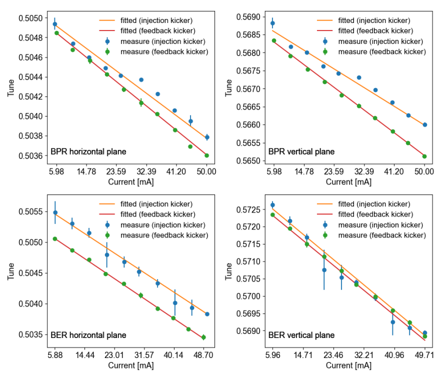

Figure 2: Transverse tune vs current.

It is clear that the vertical broadband impedances of BPR and BER are both larger than the horizontal impedances because of the chamber's octagonal cross section with the smaller vertical aperture. The impedance difference between BER and BPR is due to diversities of component structures in the rings.

Table 2: Transverse Broadband Impedance of BEPCII

Excitation	BPR (kΩ/m)		BER(kΩ/m)	
	H	V	H	V
Injection kicker	25.42	42.83	36.36	60.73
Feedback kicker	27.58	51.97	37.24	59.87
Average	26.50	47.40	36.80	60.30

TRANSVERSE COUPLED-BUNCH INSTABILITY & FEEDBACK DAMPING

A train of 118 bunches with a spacing of two empty buckets is filled in BPR and BER for higher collision luminosity. With the multi-bunches and high-current operation during the physical run, the serious transverse coupled-bunch instability induced by narrowband impedance was observed [5]. The complex tune shift of transverse coupled-bunch mode can be written as [6],

$$\Omega - \omega_\beta = -i\frac{I\omega_0}{4\pi\omega_\beta(E_0/e)}\sum_{q=-\infty}^{\infty} Z_1^\perp(\omega_q)\, J_0^2\left(\frac{\omega_q-\omega_\xi}{c}\hat{z}\right), \quad (3)$$

where Ω is the complex tune, ω_β is the transverse betatron frequency, I is the total current, c is the light speed, ω_0 is the revolution frequency, E_0 is the beam energy, $Z_1^\perp$is the transverse impedance, J_0 is the zero-order Bessel function, $\omega_q = \omega_\beta + \mu\omega_0 + pM\omega_0$ is sampling frequency of mode μ, $\omega_\xi = \frac{\omega_0\xi}{\eta}$ is related with the chromaticity ξ and slippage factor η. Equation (3) indicates when one of the sampling frequencies of a transverse coupled-bunch mode equals or is close to the resonant frequency of the narrowband impedance, the mode would be driven to be unstable sharply.

For recording the bunch-by–bunch oscillation turn by turn, a self-developed bunch-by-bunch oscillation recorder (BBR) [7-11] and the commercial feedback system [12-14] were controlled by a timing event system which can generate two completely synchronized 50 Hz square wave signals. One signal was used to trigger the BBR and the other was mixed with the front-end input signal of the feedback system to control its status, off and on. The BBR, operating at a sampling frequency of 499.8 MHz, can record the oscillation growth and damping process of every bunch when the feedback is off and on. With the bunch-by-bunch signals collected in time-domain during the oscillation growth process, a Fast Fourier Transform (FFT) was performed to identify the coupled-bunch modes. The distribution of the coupled-bunch modes was then acquired, as shown in Figs. 3 and 4.

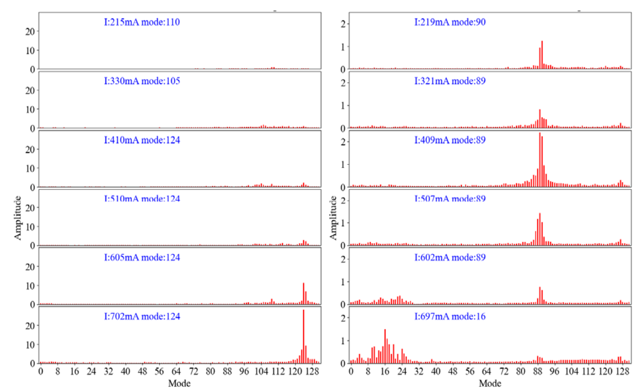

Figure 3: Horizontal (left) and vertical (right) coupled-bunch mode distribution in BPR.

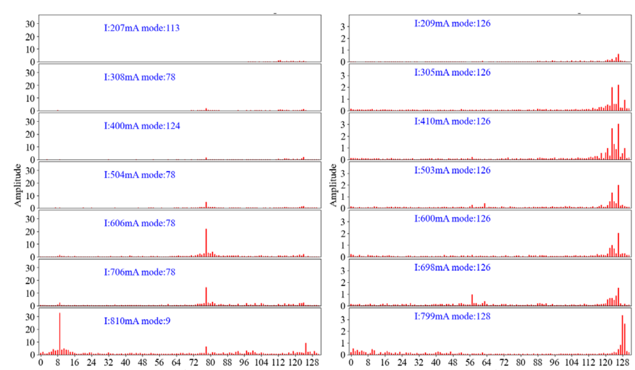

Figure 4: Horizontal (left) and vertical (right) coupled-bunch mode distribution in BER.

The horizontal mode 124 and the vertical modes 16 and 89 in BPR, as well as the horizontal modes 9 and 78 and the vertical mode 123 in BER, show stronger instabilities. The growth and damping rates of these unstable modes at different currents are obtained by fitting with an exponential function. As shown in Fig. 5, the damping rates are much greater than the growth rates, demonstrating that the powerful TFB can suppress the transverse instability effectively. The identification of the impedance sources for the instability is being carried out by simulation on various components installed in BEPCII, such as collimators, kickers, bellows and so on.

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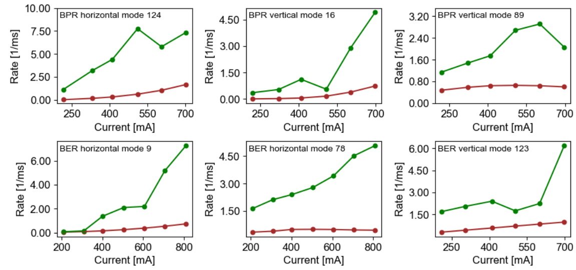

Figure 5: Transverse mode growth and damping rates vs beam current.

LONGITUDINAL COUPLED-BUNCH INSTABILITY & FEEBACK DAMPING

The serious longitudinal coupled-bunch instability appeared as early as in the commissioning phase of BEPCII. Then the commercial longitudinal bunch-by-bunch feedback (LFB) was served to its suppression. Similar to transverse expression on tune shift, the complex tune shift of longitudinal coupled-bunch mode can be written as [7]

$$\Omega - \omega_s = i\frac{2N r_0 \eta c^2}{\gamma T_0^2 \omega_s \hat{z}^2}\sum_{q=-\infty}^{\infty}\frac{Z_0^{\parallel}(\omega_q)}{\omega_q}J_1^2\left(\frac{\omega_q}{c}\hat{z}\right), \qquad (4)$$

where Ω is the complex tune, ω_s is the longitudinal synchrotron frequency, N is the bunch particle number, r_0 is the classical radius, η is the slippage factor, c is the light speed, γ is the Lorentz factor, T_0 is the revolution period, $\hat{z}$ is the bunch length, $Z_0^{\parallel}$ is the longitudinal impedance, J_1 is the first-order Bessel function, and $\omega_q = \omega_s + \mu\omega_0 + pM\omega_0$ is the sampling frequency of mode μ. The equation also indicates the unstable longitudinal coupled-bunch mode is corresponding to the longitudinal narrowband impedance which source is the cavity structure in the ring.

The apparatus for longitudinal measurement is similar, except that transverse position oscillation was replaced by longitudinal phase oscillation. The bunch-by-bunch phase oscillations were recorded when the LFB was turned off and on. Then in frequency domain, the longitudinal coupled-bunch mode distribution of BPR and BER were analyzed, as shown in Fig. 6.

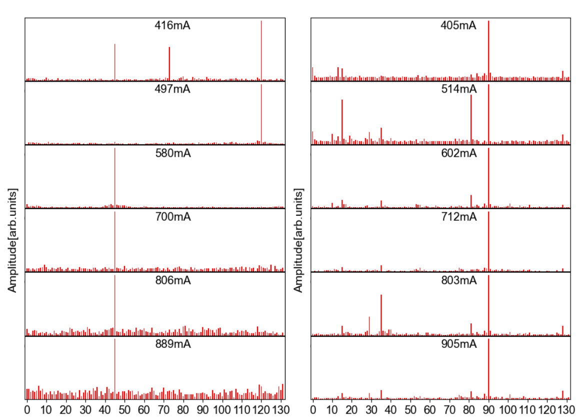

Figure 6: Longitudinal coupled-bunch mode distribution in BPR (left) and BER (right).

The modes 45, 73, and 120 in BPR, as well as the modes 15, 35, 81, 90 and 128 in BER, show stronger instabilities which means more longitudinal narrowband impedances exist in BEPCII. The growth and damping rates of these unstable modes at different currents are obtained by fitting with an exponential function. Figure 7 shows that the longitudinal instability in BPR is more serious than that in BER and the powerful LFB can suppress the instability effectively. Recent research is underway to identify the impedance sources leading to these unstable modes, mainly focusing on cavity-like components.

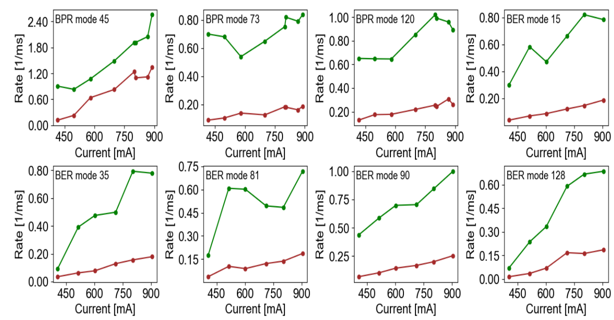

Figure 7: Longitudinal mode growth and damping rates vs beam current.

CONCLUSIONS

Measurements of bunch lengthening revealed that the longitudinal broadband impedances are 0.176 Ω for BPR and 0.153 Ω for BER, both of which are below the design impedance value of 0.27 Ω for BEPCII. Examining the tune shift effect at different currents, the transverse broadband impedances of BPR are found to be 26.50 kΩ/m in the horizontal plane and 47.40 kΩ/m in the vertical plane, and those of BER are 36.80 kΩ/m in the horizontal plane and 60.30 kΩ/m in the vertical plane, both of which are slightly larger than the design value of 18 kΩ/m for BEPCII. Fortunately, the transverse mode coupling instability current thresholds are also much higher than the currents during practical collision operation. Therefore, the transverse mode coupling instabilities of BPR and BER are also not limitations on current and collision luminosity. The longitudinal and transverse coupled-bunch instabilities in BEPCII were measured with multi-bunches by the self-developed bunch-by-bunch oscillation recorder, displaying strong instabilities in the horizontal mode 124, the vertical modes 16 and 89, and the longitudinal modes 45, 73, and 120 in BPR, as well as the horizontal modes 9 and 78, the vertical mode 123, and the longitudinal modes 15, 35, 81, 90, and 128 in BER. The growth and damping rates of these unstable modes were obtained by fitting with the exponential functions, demonstrating the powerful capability of the feedback to suppress instabilities. Research is currently being conducted to identify the narrowband impedances corresponding to these unstable modes, focusing on collimators, kickers, bellows and other cavity-like components.

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