GROWTH TIME OF THE LONGITUDINAL COUPLED BUNCH MODE BEAM INSTABILITY AT THE DUKE FEL FACILITY

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Abstract

To determine the required power of an amplifier for the longitudinal feedback (LFB) system, the growth time of the strongest longitudinal coupled bunch mode instability (CBMI) in the Duke storage ring should be measured in advance. In 2005, we measured strength of the strongest longitudinal beam instability in the Duke storage ring with four and eight symmetrically filled buckets. By analyzing measured data, the growth time of the strongest dipole mode of the longitudinal CBMI in the Duke storage ring can be estimated. At a beam energy of 274 MeV, the growth time is about 0.365 ms for a total stored beam current of 160 mA. From the measured growth time, we estimated the required power of the amplifier for the LFB system. To damp all harmful longitudinal CBMIs with an energy deviation of 0.1% (rms) within its growth time of 0.365 ms, we have to supply about 110 W (rms) to an LFB kicker whose a central frequency is 937.3875 MHz. In this paper, we describe the growth time of the longitudinal CBMI at the Duke storage ring and the estimation of the required power for the LFB system to damp all CBMIs within 0.365 ms.

INTRODUCTION

At Duke FEL laboratory, the Duke storage ring has been operated at a low beam energy of about 274 MeV with 50 filled buckets during the Photo-Emission Electron Microscopy (PEEM) user service time [1]. To increase the intensity of the High Intensity γ-ray Source (HIγS) and the PEEM user beamline, stored beam current should be high enough [2]. But due to a low beam energy and a high ring impedance, strong longitudinal and transverse coupled bunch mode beam instabilities were generated whenever stored beam current is high. In 2005, one analog transverse feedback system was installed to cure those transverse instabilities. In 2008, an iGp-64F signal processor based digital longitudinal feedback system will be installed to cure those longitudinal instabilities [3]-[5]. To determine the required power of an amplifier for the longitudinal feedback system, the growth time of the strongest longitudinal coupled bunch mode beam instability in the Duke storage ring should be measured in advance. In this paper, we describe a simple experimental method to measure the growth time of the strongest longitudinal coupled bunch mode beam instability in the Duke storage ring and estimation of a required RF power for the active longitudinal feedback system to cure the strongest longitudinal instability.

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MEASUREMENT OF INSTABILITY

Generally, the CBMI generates various phase space ($\Delta\phi - \Delta E$) oscillations such as dipole and quadrupole modes in the time domain and sidebands of the spectrum around revolution harmonics in the frequency domain [6]-[8]. To measure strength of the longitudinal beam instability in the Duke storage ring, some beam current was stored in four symmetric buckets at 350 MeV under operation of an active transverse feedback system. Then beam energy

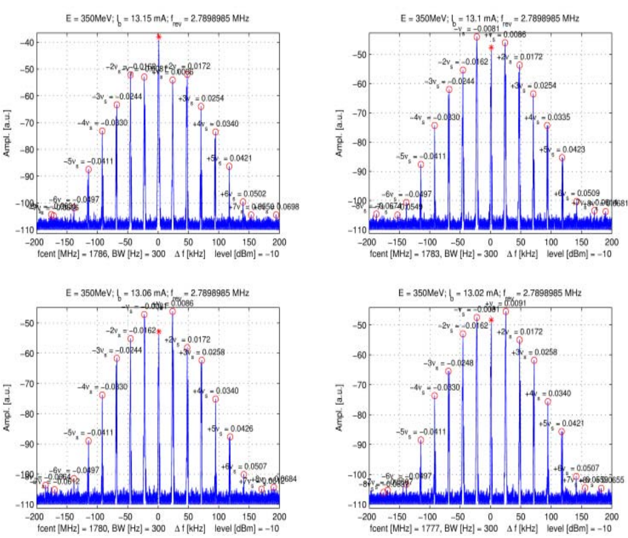

Figure 1: Undamped strong sidebands around a revolution harmonic when beam current was around 13.2 mA at 350 MeV. Here beam is aways unstable due to the strong longitudinal CBMIs.

was ramped up to about 900 MeV step-by-step while looking into amplitude of sidebands around a revolution harmonic. Whenever beam energy was increased, the harmful longitudinal CBMIs were effectively damped due to the stronger synchrotron radiation damping and reduced beam current. When there were harmful longitudinal CBMIs in the Duke storage ring, strong sidebands around a revolution harmonic were observed as shown in Fig. 1, where all sidebands were separated by the synchrotron frequency. The most strongest CBMI is the dipole mode which is separated from the revolution harmonic by the synchrotron frequency [6]-[8]. The next strongest one is the quadrupole mode which is separated from the revolution harmonic by two times of the synchrotron frequency. At a lower beam energy and a higher beam current, various modes or sidebands of the longitudinal CBMIs were observed as shown

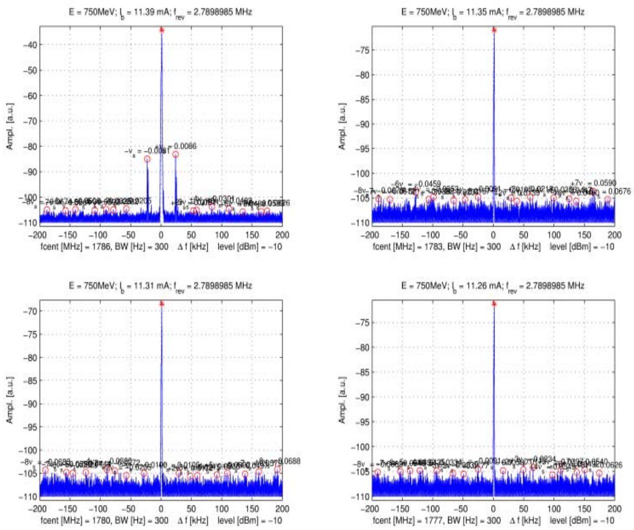

Figure 2: Damped sidebands around a revolution harmonic when beam current was around 11.4 mA at 750 MeV. Here beam is stable if beam current is lower than 11.35 mA at 750 MeV.

in Fig. 1, where there were dipole, quadrupole, sextupole, octupole, decapole, and even dodecapole modes. But those sidebands or modes were dramatically damped down to the noise level by increasing beam energy and by reducing beam current as shown in Fig. 2, where only a sideband due to the weak dipole mode CBMI was observed at a beam current of 11.39 mA and a beam energy of 750 MeV. However, the sideband was completely damped as the beam current was decayed due to scattering. Therefore all CBMIs were damped down to the noise level when beam current was about 11.35 mA. In that case, the growth rate of the longitudinal CBMI is exactly same as its damping rate, and the net growth strength of the CBMI is zero, which means that beam is stable enough against the longitudinal CBMI.

ANALYSIS OF MEASURED DATA

From the measured data, stable beam parameters were obtained as summarized in Table 1. Here I [mA] is the total stored beam current in four symmetric bunches when there is no harmful longitudinal CBMI, τ_d [ms] is the damping time due to the synchrotron radiation damping which is given by

$$\frac{1}{\tau_d} = 8.85 \times 10^{-8} \cdot \frac{f_0 E^3}{\rho}, \tag{1}$$

where $f_0 = 2.7898985$ MHz is the revolution frequency of the Duke storage ring, E [GeV] is the beam energy, and $\rho = 2.1$ m is the bending radius of the Duke storage ring [7]. For a given longitudinal CBMI, the growth time τ_g, the damping time τ_d, and the net growth time τ_n have a relation which is given by

$$\frac{1}{\tau_n} = \frac{1}{\tau_g} - \frac{1}{\tau_d}. \tag{2}$$

Table 1: Stable conditions without any CBMI.

E [GeV]	I [mA]	τ_d [ms]	G [ms·mA/GeV]
0.400	0.690	132.80	229.243
0.525	1.900	58.777	212.718
0.600	4.000	39.376	262.508
0.625	6.200	34.838	345.588
0.750	11.35	20.161	305.097

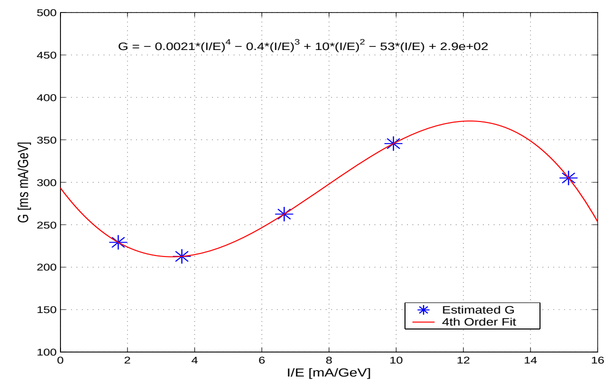

Figure 3: Plot of estimated G and its 4th order fitting result with respect to (I/E).

Therefore the net growth time τ_n is infinite when the growth time τ_g is exactly same as the damping time τ_d [7]. In that case, beam becomes stable against the longitudinal CBMI, and the growth time of the CBMI can be estimated by using that stable condition. Since the strength of a longitudinal beam instability is proportional to the total stored beam current I and inversely proportional to the beam energy E, the growth time can be given by

$$\tau_g = G \cdot \frac{E}{I}, \tag{3}$$

where G [ms·mA/GeV] is a constant [7]. As beam current is decayed, beam stability is changed from unstable status to stable one at a special beam current. In that case, τ_g is exactly same as τ_d at the beam current. From Eqs. (1) and (3), the constant G can be given by

$$G = \frac{I}{E} \cdot \tau_g = \frac{I}{E} \cdot \tau_d = 1.129943503 \times 10^7 \cdot \frac{\rho I}{f_0 E^4}. \tag{4}$$

In Table 1, G is summarized for a given beam current and a beam energy where beam is in a stable operation. And in Fig. 3, there is a plot showing estimated G and its 4th order fitting result with respect to (I/E). Here G is not a constant due to some measurement error in our measured data set and nonlinearity in the storage ring. By performing the 4th order fitting, the magnitude of G for a lower beam energy of 0.274 GeV can be estimated. If beam current is 0.690 mA at 0.274 GeV, (I/E) is 2.518 mA/GeV. In that case, G is 213.479 ms·mA/GeV from the 4th order fitting result. Therefore, from Eq. (3), the growth time τ_g is 84.781 ms for a beam current of 0.690 mA at 0.274 GeV, and it becomes $84.781 \times (0.690/160) = 0.365$ ms for a total stored beam current of 160 mA at 0.274 GeV.

AMPLIFIER FOR FEEDBACK SYSTEM

To damp all longitudinal CBMIs by an active longitudinal feedback system, a sufficient RF power should be transferred to the kicker. The required kicking voltage of the kicker is given by

$$V_{gap} = 2dT\Delta E\,, \tag{5}$$

where $d = 1/\tau_d$ is the damping rate, $T = 1/f_0$ is the revolution time, ΔE is the energy deviation in voltage due to the CBMI, which is normally within 0.1% (rms) for a given beam energy. ΔE is 0.274 MV for 0.274 GeV, and V_{gap} is 538.15 V for $\tau_d = 0.365$ ms and $f_0 = 2.7898985$ MHz. In that case, the required rms power of the amplifier to drive the kicker is given by

$$P_{rms} = \frac{|V_{gap}|^2}{2R_{sh}}\,, \tag{6}$$

where R_{sh} is the shunt impedance of the kicker [6]. From the experimental results on the bunch lengthening, the rms bunch length σ_z [ps] in the Duke storage ring is given by

$$\sigma_z = 36.9 \times (I_{single})^{1/3}\,, \tag{7}$$

where I_{single} [mA] is the beam current of a single bunch. Therefore I_{single}= 40 mA for $I = 160$ mA with four symmetrically filled buckets, and σ_z is 126.19 ps.

Since bunch length in Duke storage ring is not short, there is some difficulties to choose the central frequency of the LFB kicker [5]. However, the LFB system for the DAΦNE electron ring has been operating properly though bunch length in DAΦNE electron ring is not short either [9]. Therefore we used their experiences on the LFB operation in determining the central frequency of the LFB kicker. According to experimental results at DAΦNE electron ring, all CBMIs can be effectively damped with an active longitudinal feedback system if rms bunch length σ_z is shorter than about 15% of the RF period of the kicker [9]. Therefore, to damp all CBMIs properly in the Duke storage ring, the RF period of our kicker should be longer than 842 ps for $\sigma_z = 126.19$ ps [5]. In that case, the central frequency of our kicker should be lower than 1189 MHz. To get a margin for a longer electron bunch, we selected 937.3875 MHz for the central frequency of our LFB kicker, which gives $R_{sh} \simeq 1300\,\Omega$ under beam loading [5]. Therefore, to damp all CBMIs with an energy deviation of 0.1% (rms) within 0.365 ms, about 110 W (rms) power should be inserted to an LFB kicker with a central frequency of 937.3875 MHz. Here it is assumed that the total symmetrically filled buckets are four, the total stored beam current I is 160 mA, the beam energy E is 274 MeV, and the synchrotron radiation damping is ignored because it is too slow to damp the fast growing CBMIs at 274 MeV.

According to our another measurement data set, the growth time for eight symmetrically filled buckets is about 0.122 ms. Therefore, about 1000 W RF power will be needed to damp all CBMIs within 0.122 ms for eight symmetrically filled buckets. Here it is assumed that the total stored beam current I is 160 mA, beam energy E is at 274 MeV, and the slow synchrotron radiation damping is also ignored.

SUMMARY

When a high beam current of 160 mA is stored in four symmetric buckets at a beam energy of 274 MeV, the estimated growth time of the strongest dipole mode longitudinal beam instability in the Duke storage ring is about 0.365 ms. To damp all harmful longitudinal CBMI with an energy deviation of 0.1% (rms) within 0.365 ms, about 110 W (rms) power should be sent to an LFB kicker with a central frequency of 937.3875 MHz. According to our another measured results, the growth time for eight symmetrically filled buckets is about 0.122 ms which is about three times faster than that of our four symmetrically filled case. We expect that those harmful CBMIs can be cured by installing an iGp-64F signal processor based digital feedback system in 2008, which can supply more stable operation and much higher photon intensity during user service times of the HIγS and the PEEM.

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