ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPL187

TRANSVERSE COUPLED-BUNCH INSTABILITY DRIVEN BY THE RESISTIVE WALL IMPEDANCE AT SUPERKEKB

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Abstract

The growth time of transverse coupled-bunch instability (TCBI) in the vertical direction was measured at SuperKEKB rings. Resistive wall (RW) impedance is the primary source of driving TCBI. As a collider, special vacuum chambers are remarkable sources of RW impedance in addition to RW impedance from regular chambers. Such chambers include collimators where the chamber gap is very small and interaction region where the vertical beta functions are very large. The classical theory of TCBI based on uniform filling patterns is used to estimate the growth time and compared with experimental results.

INTRODUCTION

The resistive-wall (RW) impedance at low frequencies, which creates long-range wakefields, is a significant source of transverse coupled bunch instability (TCBI) in electron and positron storage rings. In SuperKEKB [1], transverse BxB feedback (FB) systems are installed in the main rings to suppress the CBIs [2]. While the FB systems control the CBIs, they are also used as an instrumentation tool for measuring the growth time of coupled-bunch modes. In the so-called grow/damp measurement, the FB system is intentionally turned off and on. During the time when the FB is off, the unstable CB modes grow exponentially at a rate defined by beam parameters and the driving impedance. By analyzing the unstable CB modes, one can identify the types of CBIs and their sources. The grow/damp measurement has been successfully applied at KEKB to study the resistive-wall instability and electron-cloud instability [3, 4]. During the Phase-3 commissioning of SuperKEKB, grow/damp measurements were done in the LER and HER. The typical machine parameters with $\beta^*_{y\pm}$=1/1 mm for the machine operation in 2022 are compared with the final design shown in Table 1. This paper presents the measurement results and preliminary analysis based on the classical theory of resistive-wall instability.

GROW/DAMP MEASUREMENTS

A grow/damp measurement was done in SuperKEKB HER on Jun. 29, 2021. The bunch train had a fill pattern of 1272 bunches with two gaps of missing bunches for the beam abort (see Fig. 1). The gaps are about 6.5% of the whole train and help avoid ion instability. The 1272 bunches are injected in 5120 RF buckets by every 3.06 RF buckets, a mixture of every 3 and 6 buckets. With this fill pattern, the IDs of three beam modes with the largest amplitude are 0, 1672, and 3448, as shown in the spectrum of Fig. 1. The FB system was turned off by 10 to 15 ms and then turned on, and 12 MB of data was recorded by the iGp12 digital filters [2,5]. The instability growth time and feedback damping time were extracted by transient domain analysis of the recorded data. Figure 2 shows an example of the evolution of four vertical unstable modes (i.e., modes 1671, 3447, 5119, and 3343.) at a beam current of 600 mA and vertical beta function at the

Table 1: SuperKEKB Machine Parameters for $\beta^*_{y\pm}$=0.27/0.3 mm with Final Design [1] and for $\beta^*_{y\pm}$=1/1 mm, Respectively

Parameter	Final design		2022	
	LER	HER	LER	HER
E_0 (GeV)	4.0	7.007	4.0	7.007
C (m)	3016.315		3016.315	
β^*_x (mm)	32	25	80	60
β_y (mm)	0.27	0.3	1	1
ν_x	44.53	45.53	44.524	45.532
ν_y	46.57	43.57	46.589	43.572
ν_s	0.025	0.028	0.023	0.027
α_p (10^{-4})	3.2	4.55	3.0	4.54
h	5120		5120	
$\tau_{x,y}$ (ms)	45.7	58.0	45.7	58.0
τ_s (ms)	22.8	29.0	22.8	29.0
V_{rf} (MV)	9.4	15.0	9.12	14.2
σ_{z0} (mm)	4.7	4.9	4.6	5.0
σ_{p0} (10^{-4})	7.5	6.3	7.5	6.3

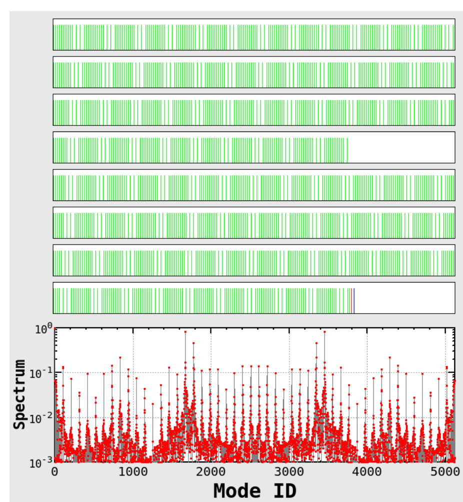

Figure 1: Fill pattern with 1272 bunches for the collision mode in SuperKEKB. The green vertical lines show the filled buckets shared by LER and HER beams. The red and blue vertical lines show the pilot bunches for LER and HER beams, respectively.

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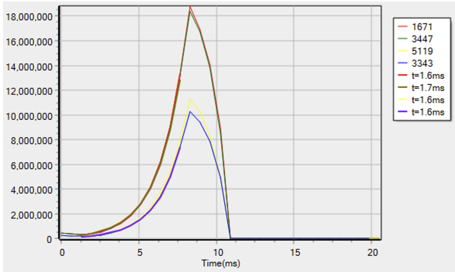

Figure 2: Evolution of vertical unstable modes with by-3.06 fill pattern in HER at a beam current of 600 mA (Jun. 29, 2021).

interaction point (IP) β^*_{y-}=1 mm. It can be seen that the three most unstable modes correspond to the three strongest beam modes but shifted by -1 and have the same growth time of around 1.6 ms. Therefore they are identified as the -1 modes that should be driven by the low-frequency resistive-wall impedance, as will be discussed in the next section.

The grow/damp measurements were also done at other beam currents and β^*_{y-}=8 mm in HER. The measured growth rates as a function of beam current are summarized in Fig. 3. The main differences in machine conditions between β^*_{y-}=8

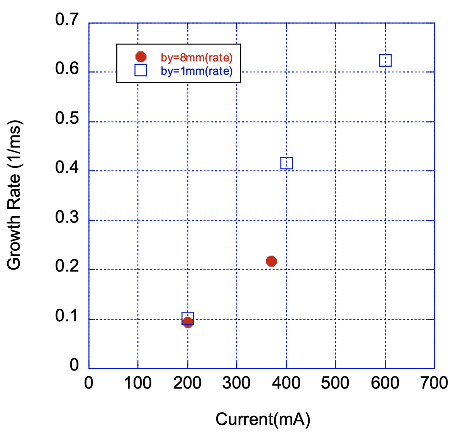

Figure 3: Measured growth rates as a function of beam current in HER (Jun. 29, 2021). The red circles and blue squares indicate measured results with β^*_y=8 and 1 mm, respectively.

and 1 mm were that the s-dependent beta functions in the interaction region (IR, see Fig. 4) and aperture settings of vertical collimators (see Fig. 5). It is suspected that the high-β IR and small-aperture collimators contribute to low-frequency transverse impedance and increase the growth rate of resistive-wall instability, as shown in Fig. 3. To confirm this suspicion, more data points are necessary to obtain a reliable slope of the growth rate as a function of beam current.

A grow/damp measurement was done in SuperKEKB LER on Mar. 28, 2022. The fill pattern of 1272 bunches is shown in Fig. 1. Similar to the previous measurements in HER, the three most unstable vertical modes were identified to be -1 modes (see Fig. 6). The growth time of these modes was around 3.8 ms at a beam current of 600 mA and vertical

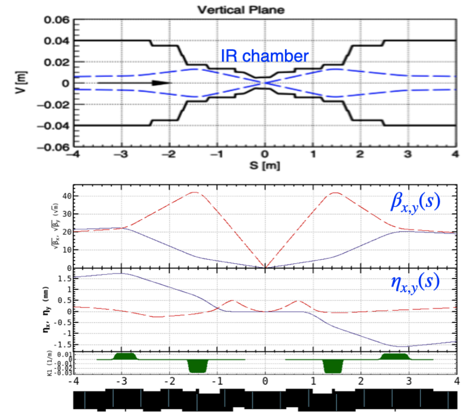

Figure 4: Vertical physical aperture of beam pipes (upper subfigure, adapted from Ref. [6]) and Twiss functions with β^*_{y-}=1 mm in the IR of SuperKEKB HER.

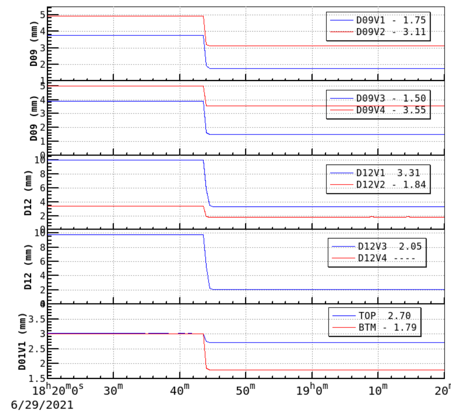

Figure 5: The aperture settings of vertical collimators in HER for β^*_{y-}=8 mm (before 18:44 PM) and β^*_{y-}=1 mm (after 18:44 PM) on Jun. 29, 2021.

beta function at the IP β^*_{y+}=1 mm. The unstable mode 4283 is suspected to be from electron-cloud instability.

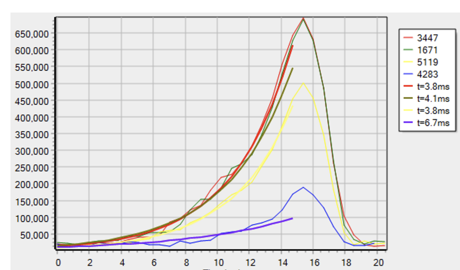

Figure 6: Evolution of vertical unstable modes with by-3.06 fill pattern in LER at a beam current of 600 mA (Mar. 28, 2022).

GROWTH TIME OF RESISTIVE-WALL INSTABILITY

The low-frequency transverse dipolar impedance model for resistive-wall instability is well known:

$$Z_1^{\perp}(k) = f_Y f_O \frac{L(\mathrm{sgn}(k) - i)}{\pi b^3} \sqrt{\frac{Z_0}{2\sigma_c |k|}}, \qquad (1)$$

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with Z_0 the impedance of free space, and other parameters indicating properties of the vacuum chamber under consideration: L the length in the longitudinal direction, b the half aperture, and σ_c the electrical conductivity. Two scaling factors are also included: f_Y the Yokoya factor, 1 for a round chamber, $\pi^2/12$ for parallel plates; f_O the scaling factor from the offset of beam orbit [7]. Here we consider f_O for the case of the parallel-plates chamber:

$$f_O = \left(1 + \frac{\pi y_0}{2b}\tan\frac{\pi y_0}{2b}\right)\frac{1}{\cos^2\frac{\pi y_0}{2b}}, \tag{2}$$

with y_0 the orbit offset. The equation is used to calculate the RW impedance of KEKB-type collimators used in HER (For their geometry, see Fig. 5 in Ref. [6]). Since only the impedance at low frequency $k \approx k_0 = 1/C$ is important for the evaluation of resistive-wall instability, the coating is neglected in the following analysis.

According to Refs. [8,9], with a gap ratio $w < 0.3$ (This is well satisfied at SuperkEKB), the simple theory with an even fill pattern works well for estimating the growth time of resistive-wall instability. For an even fill pattern with M bunches, the growth rate of μ-th mode of the bunches is given by [10]:

$$\frac{1}{\tau^{\mu}} = -\frac{Ice}{2EC}\mathrm{Re}\sum_{p=-\infty}^{\infty}\sum_i \beta_{\perp i} Z_{1i}^{\perp}((pM+\mu+\nu_{\perp 0})k_0), \tag{3}$$

with $0 \le \mu < M$. The summation over i is done for all impedance sources weighted by the local beta functions [9]. Note that $h/M = r \ge 1$ with h the harmonic number. Suppose $r = 2$, the bunch train has a by-2 fill pattern. Since a BxB FB system monitors all the RF buckets, the Fourier analysis of BxB data will show h modes instead of M modes. Assuming an equal charge for all bunches, the h modes seen by the FB system repeat their amplitudes every M modes. From this intuitive illustration, we show how the instability analysis is correlated with the Fourier analysis of measured BxB data. A rigorous correlation requires an instability analysis with an arbitrary fill pattern, including unfilled buckets.

For resistive-wall impedance of Eq. (1), the fastest mode appears at $\mu = M - \mathrm{Int}[\nu_{\perp 0}] - 1$ with $p = -1$. Here Int[] indicates taking the integer part of a variable. Correspondingly, the impedance is sampled at the negative wavenumber $k_p = (\mathrm{Frac}[\nu_{\perp 0}] - 1)k_0$ with Frac[] taking the fractional part of a variable [10]. The growth rate of the fastest mode is given by

$$\frac{1}{\tau} = -\frac{Ice}{2EC}\sum_i \beta_{\perp i} Z_{1i}^{\perp}(k_p). \tag{4}$$

For the vertical fastest mode in measurements, the total growth rate can be written as a summation of growth and damp rates from different factors, i.e.

$$\frac{1}{\tau_{yt}} = \frac{1}{\tau_{y1}} + \frac{1}{\tau_{y2}} + \frac{1}{\tau_{y3}} + \frac{1}{\tau_{ySR}} + \frac{1}{\tau_{yHT}}, \tag{5}$$

with τ_{y1} from the regular chambers, τ_{y2} from the IR, τ_{y3} from the collimators, τ_{ySR} indicating the synchrotron radiation (SR) damping, and τ_{yHT} due to slow head-tail damping [11, 12]. Here we assumed that the contributions of 3D structures to the low-frequency impedance are negligible.

For HER with β_y^*=1 mm and I=600 mA, the growth times are calculated as follows. 1) For regular chambers (see Fig. 1 of Ref. [13]), we take b=25 mm, L=3011 m, σ_c=5.8 × 10^7 S/m for copper, the average beta function $\overline{\beta}_y$=25.8 m for the arc and straight sections. The growth time of the fast mode is τ_{y1}=1.7 ms. 2) For the IR, τ_{y2}=0.8 ms. 3) For vertical collimators, τ_{y3}=5.3 ms. 4) For SR damping, τ_{ySR}=-58 ms. 5) For head-tail damping, τ_{yHT} is unknown due to lack of transverse impedance model. We obtain a total growth time of τ_{yt}=0.5 ms, a factor of 3 smaller than the measurement of τ_{ye}=1.6 ms. While the growth time τ_{y1} from regular chambers seems good enough to explain the measurement.

For LER with β_y^*=1 mm and I=600 mA, the growth times are calculated as follows. 1) For regular chambers (see Fig. 1 of Ref. [13]), we take b=45 mm, L=3011 m, σ_c=3.8 × 10^7 S/m for aluminum, the average beta function $\overline{\beta}_y$=25.3 m for the arc and straight sections. The growth time of the fast mode is τ_{y1}=6.7 ms. 2) For the IR, τ_{y2}=1.1 ms. 3) For vertical collimators (For their geometry, see Fig.6 in Ref. [6]), τ_{y3}=23.1 ms. 4) For SR damping, τ_{ySR}=-45.7 ms. 5) For head-tail damping, τ_{yHT}=-17.9 ms with vertical chromaticity ξ_y=1.5 (This estimate uses a short-bunch wake model for the whole ring and is roughly consistent with the findings in Refs. [14, 15]). The total growth time is τ_{yt}=1.0 ms, a factor of 3.8 smaller than the measurement of τ_{ye}=3.8 ms. While the growth time τ_{y1} from regular chambers is 6.7 ms, that seems not enough to explain the measurement.

SUMMARY

From grow/damp measurements, the vertical unstable modes of CBIs at SuperKEKB HER and LER were attributed to RW instability. The measurements in HER showed that the IR and collimators might contribute to RW instability. The classical model of RW instability is applied to calculate the growth time. For HER, the impedance of regular racetrack chambers can explain the measured growth time. But for LER, the impedance of regular round chambers cannot explain the measurement. The simple model for the resistive-wall impedance is also applied to high-beta IR and collimators (Note that the beam pipes of IR and collimators are 3D structures with lengths much shorter than the circumference of the rings.), showing an overestimate of the growth time of the resistive-wall instability. It suggests that the validity of the simple RW impedance model for 3D structures needs to be investigated.

ACKNOWLEDGEMENTS

We thank the SuperKEKB team for their constant support of our work. Special thanks are due to K. Oide, G. Bassi, A. Blednykh, A. Natochii, K. Ohmi, Y. Ohnishi, Y. Funakoshi, N. Wang, Y. Zhang, et al. for fruitful discussions.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPL187

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