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LONGITUDINAL COUPLED BUNCH INSTABILITY IN JLEIC*

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Abstract

The high luminosity performance of JLEIC requires maximum number of bunches in the collider rings with moderate single bunch charges. This makes the coupled bunch instability an important issue for the JLEIC beam stability. For the ion beam, the fast growth rate of the longitudinal coupled-bunch instability (LCBI) sets unprecedented demands for the fast bunch-by-bunch feedback system. In this paper, we identify the most offensive mode in the HOMs for both the JLEIC electron and ion rings. This will assist the RF cavity design in improving the HOM damping and in reducing the severity of LCBI.

INTRODUCTION

JLEIC design aims at luminosity of 10^{33}~10^{34} cm^{-2}s^{-1} for the center of mass energy of 30~140 GeV and for a wide range of ion species [1, 2]. The current baseline parameters are set for the electron beam at collision energies E_e=3, 5, 10 GeV and for the proton beam at energy E_p=100 GeV [3]. Besides other crucial features of the JLEIC luminosity concept, such as employing short bunches and low β_y^*, as well as the crab crossing at $\theta = 50$ mrad , the high luminosity is achieved by the bunch configuration of up to 3460 bunches in the rings with moderate charge per bunch. Consequently the electron and ion beams are vulnerable to the longitudinal and transverse coupled bunch instabilities.

Preliminary estimations [4] for the coupled bunch instabilities were performed using ZAP [5], where PEPII RF cavities and their relevant HOMs were used for the electron beam, and a recent low-cost RF cavity design (a two-cell RF cavity with coaxial HOM damping) is assumed for the proton beam. The CBI growth time of a few milliseconds implies the necessity of the state-of-art bunch-by-bunch fast feedback system (FBS), as typically used in modern storage-ring light sources. However, the fast bunch repetition rate of the ion beam takes the JLEIC ion ring to a new parameter regime, and the millisecond damping time for 100 GeV proton beam implies unprecedented number of FBS kickers in the ion ring, which could result in a big increase of the broadband impedances. In this paper we take a close look [6] at the LCBI analysis for the JLEIC ion beam in order to identify the most harmful HOM. This information will be useful for the RF cavity design for further improving the HOM damping, so as to alleviate the demands on FBS kickers for mitigation of LCBI.

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GROWTH RATE FOR LCBI

The LCBI instability originates from the HOM impedance of the RF cavities in a storage ring. Here we outline the formula for the LCBI growth rate. Given a set of HOMs from RF cavities characterized by $\{R_s^{(i)}, Q^{(i)}, \omega_r^{(i)}\}$ for i=1 to n, and ignoring the interference between different modes, we have the (upper limit of) total impedance as

$$Z_{\|}(\omega) = \sum_{i=1}^{n} \frac{R_s^{(i)}}{1 + iQ^{(i)}\left(\frac{\omega_r^{(i)}}{\omega} - \frac{\omega}{\omega_r^{(i)}}\right)}.$$

The effective impedance depicts the sampling of impedance by the bunch power spectra (for an evenly distributed bunch filling pattern). Assuming the ring has even fill of bunches, the effective impedance is [7]

$$\left[\frac{Z_{\|}}{n}\right]_{\rm eff}^{\mu,a} = \sum_{p=-\infty}^{\infty} \frac{Z_{\|}(\omega_p'')}{(\omega_p''/\omega)} \frac{h_a(\omega_p'')}{S_a},$$

with $\omega_p'' = (pM + \mu + a\nu_s)\omega_0$ the side band of the a-th single bunch mode for the μ-th coupled-bunch mode and the p-th harmonic of the bunch repetition rate, and

$$S_a = \sum_{p=-\infty}^{\infty} h_a(\omega'').$$

For a parabolic single-bunch longitudinal charge distribution, the bunch power spectra for the a-th single-bunch mode is

$$h_a(\omega) = (a+1)^2 \frac{1 + (-1)^a \cos(\omega/\omega_b)}{\left[(\omega/\pi\omega_b)^2 - (a+1)^2\right]^2}$$

with $\omega_b = \beta c/(2\sqrt{2}\,\sigma_z)$ the bunch frequency; while for a Gaussian bunch, we have

$$h_a(\omega) = \left(\frac{\omega}{\omega_b}\right)^{2a} \exp\left[-\left(\frac{\omega}{\omega_b}\right)^2\right]$$

with $\omega_b = \beta c/\sigma_z$ and σ_z the rms bunch length. The growth rate of LCBI for the (μ, a) mode is then

$$\tau_{\mu,a} = C \left[\frac{Z_{\|}}{n}\right]_{\rm eff}^{\mu,a}, \qquad (1)$$

for $$C = \frac{I_b \omega_0^2 \eta}{6(L/2\pi R)^3 2\pi\beta^2 (E/e)\omega_s},$$

with $L = 2\sqrt{2}\sigma_z$ for parabolic bunches and $L = 2\sqrt{\pi}\sigma_z$ for Gaussian bunches.

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LCBI FOR THE ION BEAM

The longitudinal HOMs for the JLEIC ion ring two-cell cavity design is listed in Table 1 [8]:

Table 1: Longitudinal HOMs for Ion Ring RF Cavities

f [MHz]	Rs [Ohm]	Q
940.8	7.98e06	2.98e06
1771.9	2.25e04	5643.9
1814.0	1.00e05	5265.5
2894.8	3.33e04	9172.4
3079.4	2.23e02	2.65e4

The corresponding resonance peaks for $\mathrm{Re}\,Z_{\parallel}$ are shown in Fig. 1 (for 34 cavities with the de-Qing factor of 10).

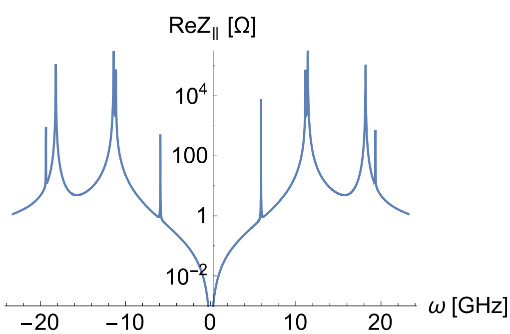

Figure 1: $\mathrm{Re}\,Z_{\parallel}(\omega)$ vs. ω for HOMs in Table 1.

For parabolic ion bunches, the summand of effective impedance is shown in Fig. 2 for two different coupled bunch modes $\mu = 276$ (green) and μ=2764 (red) and for low positive integer p.

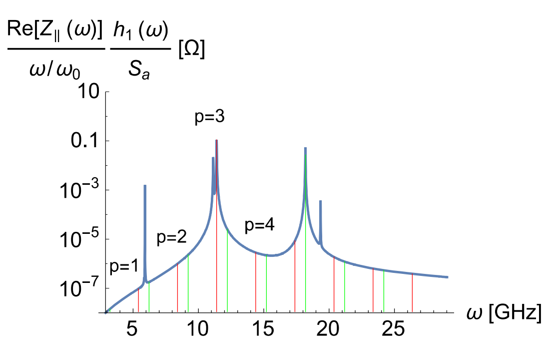

Figure 2: Summand of effective impedance for two different coupled-bunch modes (ion ring)

Note that the bunch frequency $\omega_p'' = (pM + \mu + \nu_s)\omega_0$ for $p=3$ and $\mu = 2764$ hits right on spot with the 3rd RF cavity HOM, as shown in the zoom-in view (Fig. 3). As a result, the effective impedance and the LBCI growth rate are almost singly contributed by this particular HOM resonance, yielding $\tau = 5.9$ ms. Fig. 4 shows the dependence of growth rate on the coupled-bunch mode.

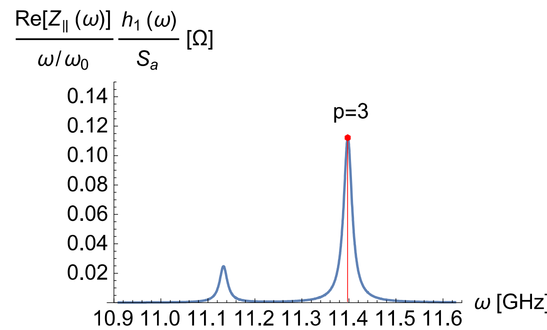

Figure 3: Zoom-in view of the summand of effective impedance for p=3 and $\mu = 2764$.

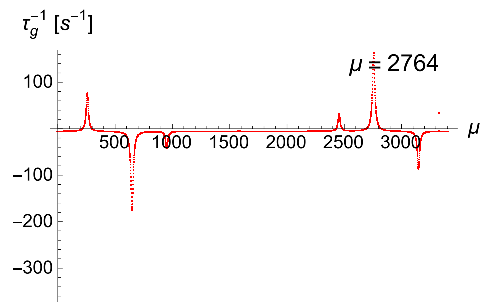

Figure 4: LCBI growth rate vs. the coupled-bunch μ for the JLEIC ion beam, by direct summation over p (red) or by analytical results [5] (blue).

This result is suggestive for the RF cavity design in the need to further damp the 3rd HOM mode for the current low-cost two-cell cavity. Other options, such as single-cell cavities, with the more efficient waveguide dampers or on-cell dampers, are expected to have the capability to bring the HOM down.

LCBI FOR THE ELECTRON BEAM

Next we perform the same analysis for the HOM effects on the LCBI growth rate for the JLEIC electron beam at E_e=3 GeV. The HOMs of PEPII RF cavity is given in Ref. [9], and the corresponding resonance peaks for $\mathrm{Re}\,Z_{\parallel}$ are shown in Fig. 5 (here only one cavity is used).

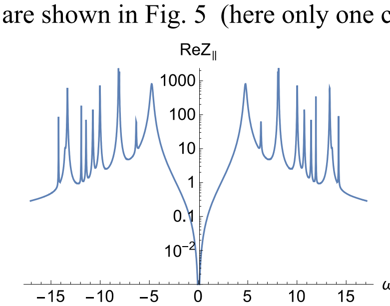

Figure 5: $\mathrm{Re}\,Z_{\parallel}(\omega)$ vs. ω for HOMs in the PEPII RF Cavities

For Gaussian electron bunches, the summand of the effective impedance is shown in Fig. 6 for two different

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coupled bunch modes $\mu = 249$ and μ=2491 and for low positive integer *p*.

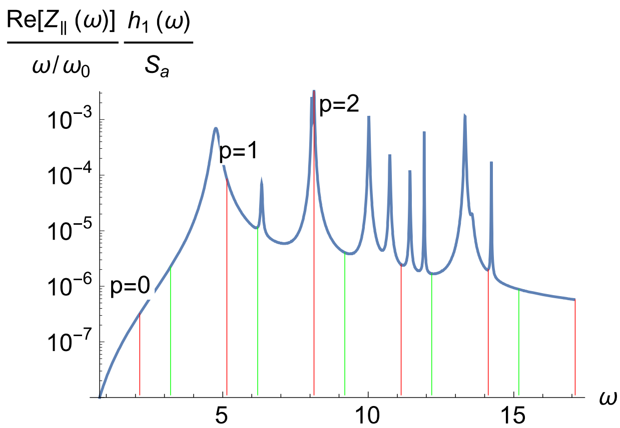

Figure 6: Summand of effective impedance for two different coupled-bunch modes (electron ring).

Interestingly, similar to the case of the for the ion beam, here we find good overlap of the bunch frequency for p=2 and $\mu = 2941$ with the 3rd HOM mode, as the zoom-in view shown in Fig. 7.

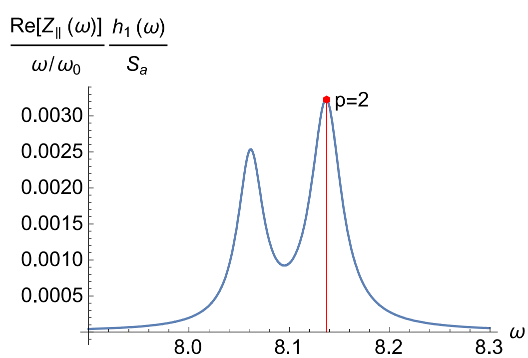

Figure 7: Zoom-in view of the summand of effective impedance for p=2 and $\mu = 2491$.

The dependence of growth rate on the coupled-bunch mode is shown in Fig. 8. Notice the highest LCBI growth rate is for $\mu = 2491$, which is singly dominated by the particular HOM resonance that overlaps with *p*=2 harmonic, yielding $\tau = 3.2$ ms. Even though for the 3 GeV electron beam, *C* in Eq. (1) is 70 times larger than that for the 100 GeV proton beam, and both cases have one HOM resonance peak overlapping with one coupled-bunch frequency, the large amplitude of HOM impedance for the ion ring for the low-cost ion cavity design makes the ion beam LCBI growth rate only half of that for the electron beam.

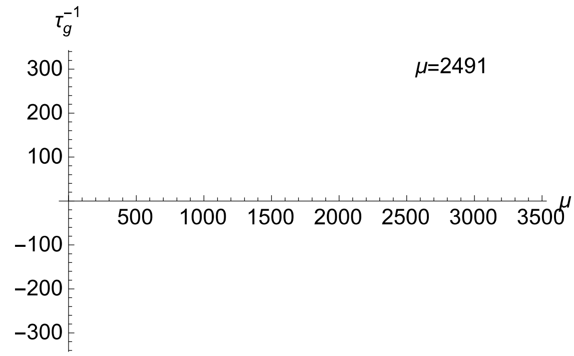

Figure 8: LCBI growth rate vs. the coupled-bunch μ for the JLEIC electron beam.

CONCLUSION

Detailed studies for the LCBI growth rate, for both the electron and ion beams in JLEIC, are performed in this paper. This study identifies the particular HOM mode that has dominate contribution to the LCBI growth rate, and allows the RF cavity design to make design choices for minimizing the growth rate and thus alleviate the demands on the longitudinally fast feedback system. Other options of cavity design, such as single-cell cavities with more efficient waveguide dampers or on-cell dampers, are also under consideration. More careful modelling of the coupled bunch instabilities is to be carried out for the realistic uneven bunch pattern (with injection/ejection gaps and ion clearing gaps), as well as for the joint effects of HOMs from both the accelerating/focusing RF cavities and the crab cavities [10].

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