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Study of beam-beam interaction in FCC-ee including updated transverse and longitudinal Impedances

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Abstract. Beam-beam interaction in FCC-ee can be seriously affected by the vacuum chamber coupling impedance resulting in a safe tune areas reduction, tune shifts and spread, bunch length and energy spread variation. The interplay of the two effects has a drastic impact on the stability of colliding bunches and respectively on the achievable luminosity. In this paper, beam-beam collisions in FCC-ee with 4 interaction points are studied including the updated transverse and longitudinal impedances.

1. Introduction

After the crab-waist concept proposal [1] and its successful test in DAΦNE [2], this collision scheme has been considered as the baseline design option for the future e+e- circular colliders, such as FCCee [3], CEPC [4] and SuperTC [5].

Recently it was found that new coherent head-tail instability, called X-Z instability, can affect the stability of colliding beams in FCCee [6]. Further studies relying on both numerical simulations [7] and analytical analysis [8] have revealed that the longitudinal impedance may strengthen this instability. So different mitigation techniques have been considered [9, 10] and parameter optimizations have been therefore performed to cope with the instability.

Following the design process of FCCee, the main machine parameters have been evolving and the impedance budget has been updated [11, 12]. An accompanying paper of these proceedings is dedicated to impedance calculation and single-beam collective effect studies [12]. In this paper, we focus on the combined effect of beam-beam interaction and the updated impedance, taking into account both longitudinal and transverse impedances. The code IBB [13, 7] is used for the simulations and in Table 1 we report the reference parameter list.

2. Impedance update

As the machine design progresses, so does the impedance model. Up to now, we have evaluated the contribution of different devices, and the main sources were found to be produced by the resistive wall, the collimation system and the bellows. For all the cases in which there is no cylindrical symmetry, we have also evaluated the contribution of the quadrupolar (detuning) impedances. In particular, the transverse impedance has recently undergone a significant

Table 1. Main Parameters (FCCee-Z)

Parameter	
Beam Energy	45.6 GeV
Bunch Population (10^{10})	24
Emittance ($\epsilon_{x,y}$)	0.71 nm / 1.42 pm
β_x^*/β_y^*	0.1 m / 0.8 mm
Bunch Length [natural/bs]	4.38/16.6 mm
Energy Spread [natural/bs] (10^{-4})	3.8/13.8
Synchrotron Tune	0.00925
Damping Rate (x/y/z) (10^{-4})	1.07/1.07/2.14
Half Crossing Angle	15 mrad
Piwinski Angle	29.5
Beam-Beam Parameter (x/y)	0.0019/0.11

increase due to the contribution of the collimation system. However, we must highlight that only the resistive wall term of the collimators has been included in the model so far, and work is in progress for the geometrical contribution.

In the following simulation study, we will first evaluate the effect of horizontal impedance (dipole+detuning) and then will take into account the vertical one.

3. Effect of horizontal impedance

The horizontal beam-beam cross-wake function has been given in Eq. (12) of Ref. [14],

$$W_x^{(-)}(z) = -\frac{N^{(+)}r_e}{\gamma^{(-)}\bar{\sigma}_x^2}\left\{1 - \frac{\sqrt{\pi}\theta_p z}{2\bar{\sigma}_z}\mathtt{Im}\left[w\left(\frac{\theta_p z}{2\sigma_z}\right)\right]\right\}, \tag{1}$$

where where $N^{(+)}$ is the number of particles of the e^+ bunch, $\gamma^{(-)}$ is the relativistic energy of the e^- bunch, r_e is the classical radius of the electron, $\bar{\sigma}_x^2 = (\sigma_x^{(+)2} + \sigma_x^{(-)2})/2$, $\theta_p = \theta_c\sigma_z/\bar{\sigma}_x$ is the Piwinski angle and w is the complex error function. The corresponding cross impedance is obtained by the Fourier transform of the wake force,

$$Z(\omega) = i\int_{-\infty}^{\infty} W(z)e^{-i\omega z/c}\frac{dz}{c}. \tag{2}$$

The beam-beam cross impedance is purely imaginary and, in Fig. 1, we compare it with the machine impedance. We can see that in most of the beam spectrum range of interest (< 50 GHz) the cross impedances dominate, while in the very low-frequency region, the coupling impedances dominate. One should also remember that the beam-beam interaction is very local, while the machine impedance is supposed to be evenly distributed in the ring. The local property of cross impedance induces the X-Z instability [14].

Here we're interested in the combined effect of machine impedance and cross impedance. In our simulation, the beam-beam interaction is modelled with strong-strong Gaussian approximation instead of directly using the cross impedance.

Figure 2 shows the horizontal size blowup versus the horizontal tune. As it can be seen, the width of stable tune areas is practically not affected by the transverse impedance (including both dipole and detuning wakes). However, the instability is more severe when the transverse impedance is included, as shown in Fig. 3. The relative horizontal beam size blowup is limited

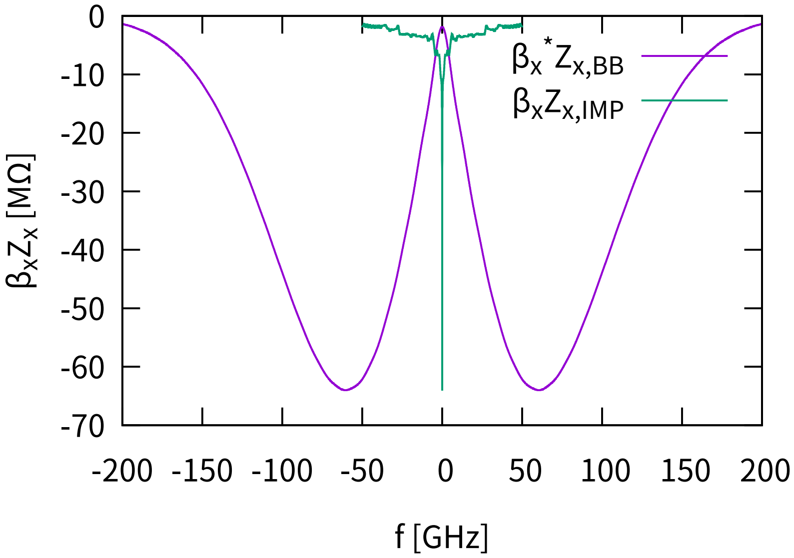

Figure 1. Comparison of horizontal machine impedance (quarter part) and horizontal beam-beam cross impedance, where the impedances have been weighted by the local β function.

to several units if the transverse impedance is not included in the simulations. Instead, when the transverse impedance is taken into account, the RMS beam size growth is much larger and the saturation of the blowup is not yet observed even at $\sigma_x/\sigma_{x0} > 15$. The latter situation is more similar to the beam blowup due to a TMCI-like instability, or we could say it is a combined effect of the X-Z instability and the TMCI instability.

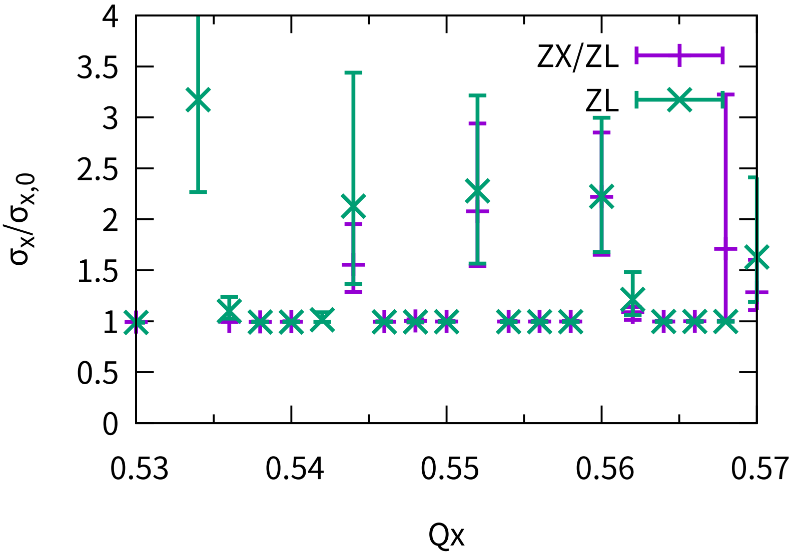

Figure 2. Horizontal beam size blowup considering Z_x and Z_l.

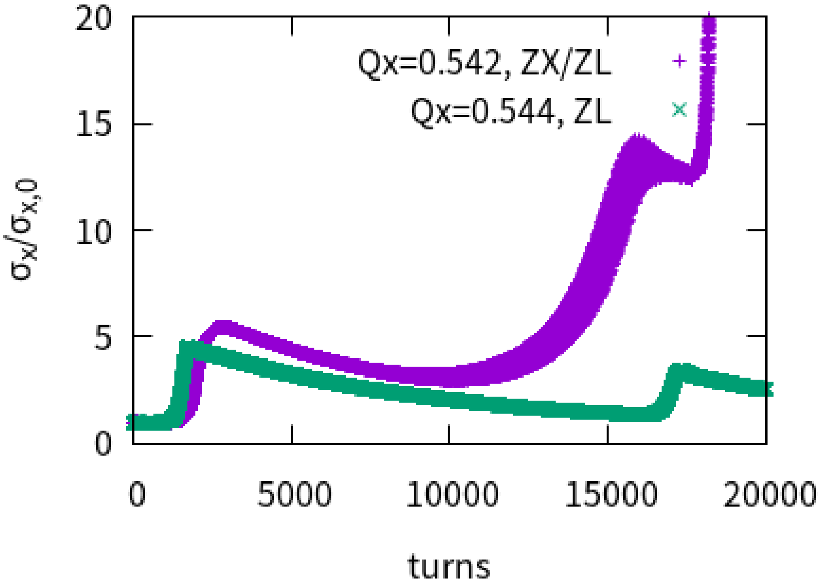

Figure 3. Evolution of horizontal RMS size with and without horizontal impedance

4. Effects due to both transverse impedances

Here we include also the vertical impedance in the simulations and start with the horizontal tune luminosity scan fixing the vertical tune at 0.600. Figure 4 compares the luminosity obtained with Z_x alone and with both transverse impedances Z_x and Z_y included. As it can be seen, the addition of the vertical impedance results in unstable collisions for the horizontal tunes far from the half-integer or closer to the vertical tune. A strong vertical instability is observed in such a case with a dramatic vertical beam blowup, see Fig. 5. Then for the fixed horizontal tune $Q_x = 0.556$ we perform the vertical tune scan, see Fig. 6. As it is seen, the vertical motion becomes stable for the vertical tunes Q_y exceeding 0.61, when the gap between Q_y and Q_x is greater than 0.054.

It could be seen that the vertical instability also depends on the horizontal tune. A common knowledge is that transverse coupling may change the behaviour of single bunch instability. With crab-waist collision, one particle's interaction point depends on its horizontal amplitude. One hypothesis is that there exists a coupling resonance between the lower-order head-tail modes of horizontal oscillation and vertical oscillation. It seems the machine transverse impedances enhance the X/Y coupling and induce serious vertical instability. The underlying physics will be studied in future work.

Referring to the work of horizontal cross wake [14], the vertical cross wake has also been obtained [15],

$$W_y^{(-)}(z) = -\frac{N^{(+)}r_e}{\gamma^{(-)}}\frac{1}{\bar{\sigma}_x\bar{\sigma}_y}\exp(-\frac{\zeta^2}{4}), \tag{3}$$

where $\zeta = \theta_p z/\sigma_z$. Figure 7 shows the comparison between corresponding cross impedance and machine impedance in the vertical direction. Also for the vertical cross impedance there exists only the imaginary part. It seems the beam-beam impedance would enhance the total ring impedance besides its local property.

Finite chromaticity is often used to mitigate TMCI instability. We try $Q_y' = 5$ in the vertical direction and scan the vertical tune. The results are presented in Fig. 8, which shows that

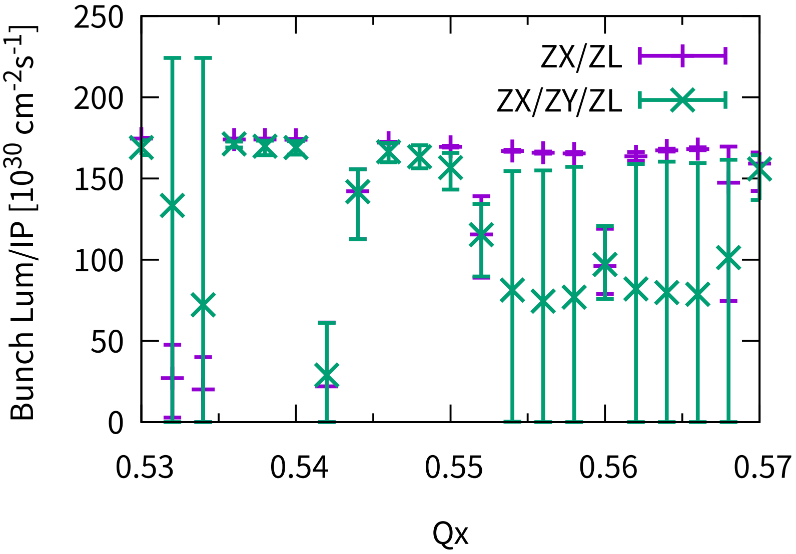

Figure 4. Luminosity versus horizontal tune with and without Z_y (Qy=0.600).

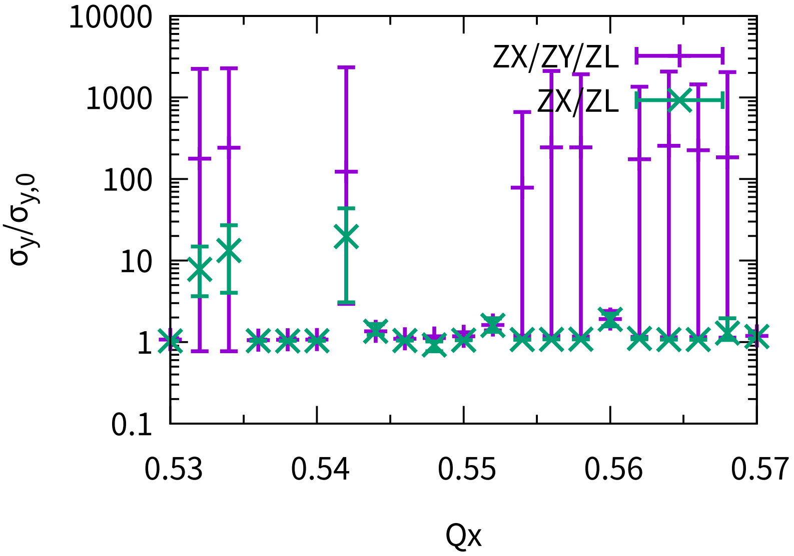

Figure 5. Vertical beam size versus horizontal tune with and without Z_y. (Qy=0.600).

finite chromaticity also may be an effective method to mitigate the instability induced by the combined effect of beam-beam interaction and machine impedance.

At $Q_y = 0.610$, we simulate the bootstrapping injection with a horizontal tune scan considering all impedances. When the bunch population increase to about 8e10, there exists vertical beam size blowup, and we use finite vertical tune chromaticity for higher bunch current to suppress the instability. Figure 9 shows the horizontal beam size blowup during bootstrapping injection. It is found that X-Z instability has been mitigated very well with the present machine parameters, and the present impedances do not bring much trouble so far.

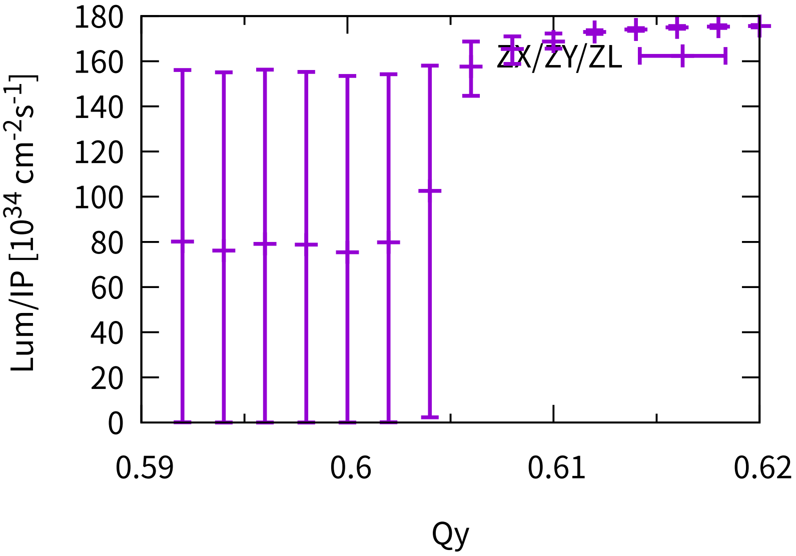

Figure 6. Luminosity versus vertical tune with $Z_x/Z_y/Z_l$ (Qx=0.556).

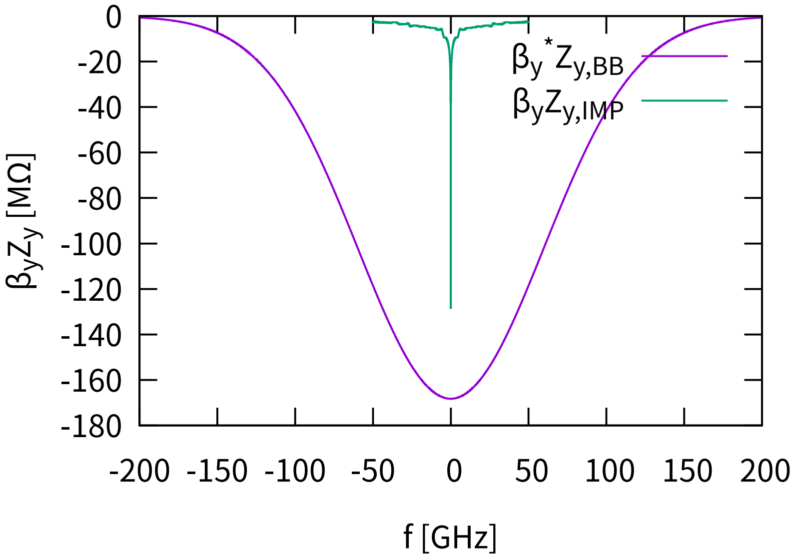

Figure 7. Comparison of vertical machine impedance (quarter part) and horizontal beam-beam cross wake impedance, where the impedances have been weighted by the local β function.

5. Summary

In this paper, the interplay between beam-beam interaction and the beam coupling impedance in FCC-ee is studied for the present machine parameters using the updated impedance model. In addition to the longitudinal impedance the effects of both transverse impedances are investigated. In particular, it is shown that the X-Z instability gets stronger when the horizontal impedance is included, although the stable tune areas are practically not affected. In addition, a new vertical instability can arise when the vertical impedance is taken into consideration. This instability may limit the choice of betatron working points available for stable collider operation. Hopefully, it is found that the positive vertical chromaticity is an effective tool to suppress the

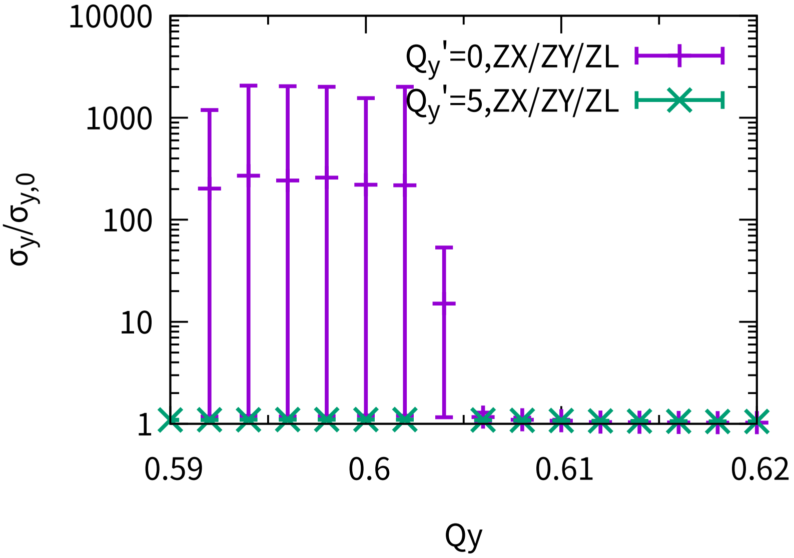

Figure 8. Mitigation of vertical coherent instability from finite linear tune chromaticity and with $Z_x/Z_y/Z_l$. (Qx=0.556)

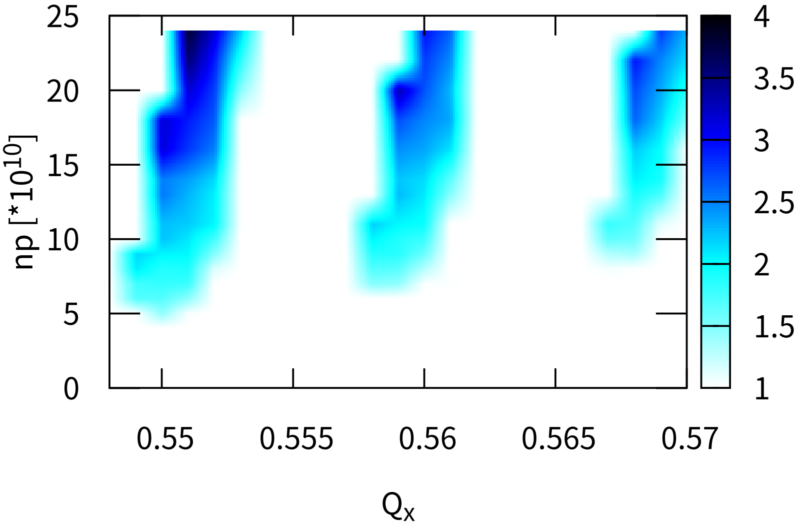

Figure 9. Horizontal beam size blowup during bootstrapping injection with $Z_x/Z_y/Z_l$ ($Q_y = 0.610$).

vertical instability and a stable collider operation can be achieved for the considered machine parameters and the presently evaluated impedance. However, it is believed that the impedance budget will certainly increase following the evolution of the FCC-ee vacuum chamber design and adding impedance contributions of other vacuum chamber components and accelerator hardware. So the study of the combined effects and their mitigation will continue in the future.

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