Mitigation of Coherent Beam Instabilities in CEPC

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Abstract

The collective beam instabilities are potential restrictions in the Circular Electron Positron Collider (CEPC) to achieve high luminosity performance. These instabilities can induce beam quality degradation or beam losses. Different strategies used to mitigate these effects are discussed. The impedances of the dominant contributors are carefully designed and optimized to either reduce the parasitic power dissipation or increase the beam instability threshold. The bunch filling patterns are also optimized to fight the beam ion instability, the electron cloud build up and the transient beam loading effect.

INTRODUCTION

Potential restrictions from collective beam instabilities include beam current thresholds and beam quality degradations. On the one hand, the beam current thresholds are mainly determined by instability-induced beam losses and heat load in vacuum components due to the parasitic power dissipations. On the other hand, the beam quality degradations include bunch lengthening and beam energy spread increase, synchrotron or betatron tune shift, emittance blow-up, etc.

CEPC is designed to cover beam energies to produce Z and Higgs bosons [1]. Therefore, different operational scenarios need to be considered. The design of the beam parameters for the Z boson shows most critical requirements on the beam instabilities, due to the lowest beam energy, highest beam current, slowest radiation damping, and synchrotron oscillations. In order to estimate the influence of these effects, the impedance model of the CEPC collider is developed. Based on the impedance studies, critical beam instability issues for the Z mode of operation and their mitigations are discussed. The main beam parameters are listed in Table 1.

Table 1: Main beam parameters of CEPC Z

Parameter	**Symbol, unit**	**Value**
Beam energy	E, GeV	45.5
Circumference	C, km	100
Beam current	I_0, mA	461.0
Bunch number	n_b	12000
Momentum compaction	α_p	1.11×10^{-5}
Betatron tune	ν_x/ν_y	363.1/365.22
Synchrotron tune	ν_s	0.028
Radiation damping	$\tau_x/\tau_y/\tau_z$, ms	843/843/436

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IMPEDANCE MODELING

For the impedance modeling, the dominant impedance contributors are first identified, including both with large impedance and with small impedance but in large numbers. Meanwhile, the impedances of the components are carefully designed and optimized to either reduce the parasitic power dissipation or increase the beam instability threshold.

The resistive wall (RW) impedance is the dominant contribution to the total impedance when the goemetric impedances (GEO) have been kept low by careful design. Nonevaporable getter (NEG) coating is adopted on the copper beam pipe for vacuum pumping and electron cloud mitigation. The influence of the coating thickness on the longitudinal and transverse impedances is studied [2], as shown in Fig. 1 and Fig. 2. The solid and dashed lines correspond to the real and imaginary impedance, respectively. Here, the conductivity of NEG used in the impedance evaluation is 1 MS/m [3].

The results show that both longitudinal and transverse impedances are reduced with thinner NEG coating. In the frequency range of interest (the bunch spectrum extends to ~40 GHz), the NEG coating shows significant influence on the imaginary part of the impedances, which are mainly responsible for bunch lengthening and tune shift, and less impact on the real part, which emphasizes beam energy loss and instability growth rate. In CEPC, coating thickness of 0.2 µm has been chosen to reduce the impedance from resistive wall.

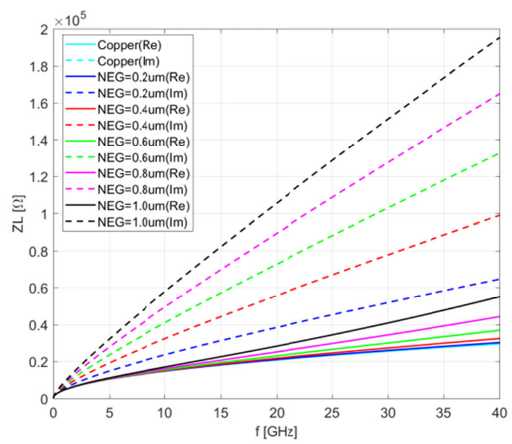

Figure 1: Longitudinal impedance with different thickness of NEG coating (the solid and dashed lines correspond to the real and imaginary impedance, respectively).

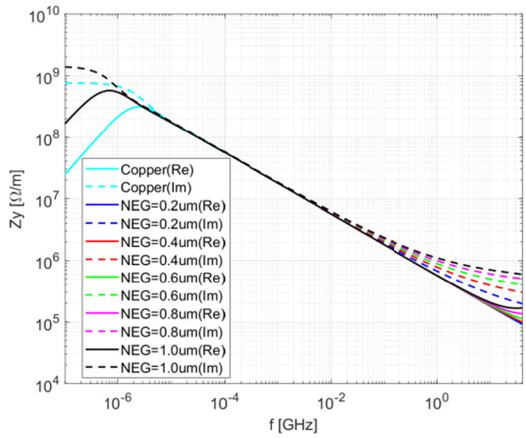

Figure 2: Transverse impedance with different thickness of NEG coating (the solid and dashed lines correspond to the real and imaginary impedance, respectively).

Since only the impedance in the frequency range of the bunch spectrum will affect the beam, the effective broadband impedances are calculated to quantitatively describe the influence of the coating thickness. With rms bunch length of 3 mm, the variations of the longitudinal and transverse effective impedance with different coating thickness are shown in Fig. 3 and Fig.4.

With thickness of NEG coating from 0 to 1 μm, the longitudinal impedance is increased by a factor of ~4 and the transverse kick factor is increased by a factor of ~3. However, the loss factor is only increased by ~20%. Here, we should note that the specific values are quite dependent on the bunch distribution and the radius of the beam pipe.

For the geometrical impedances, RF shielding is adopted for cavity structures, such as flanges, bellows, pumping ports, etc. Taper transitions of less than 1/10 are adopted at aperture discontinuities. Meanwhile, high order mode (HOM) damping is considered for resonant structures, such as the RF cavities, interaction region (IR) and the electro-separators.

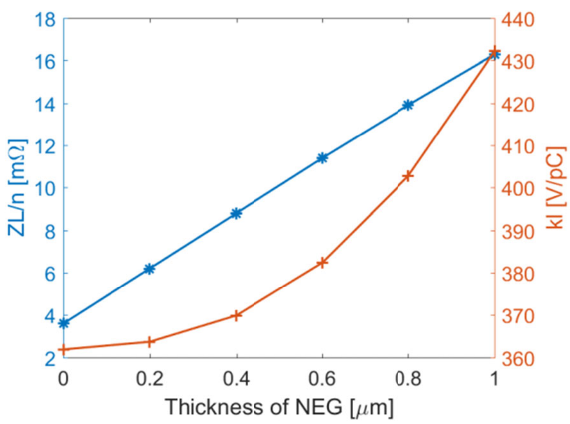

Figure 3: Dependence of the longitudinal effective impedance and loss factor on the thickness of NEG coating.

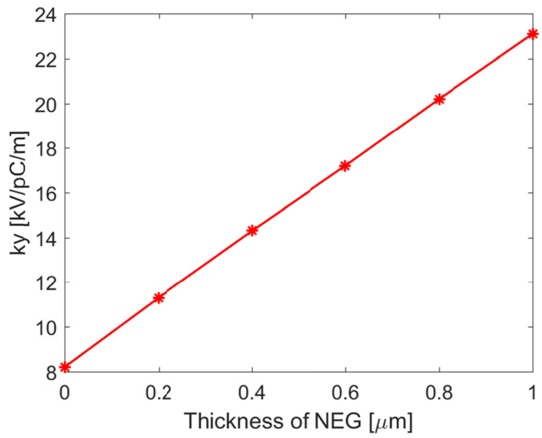

Figure 4: Dependence of the transverse kick factor on the thickness of NEG coating.

Table 2 shows the impedance budget of the main contributors with rms bunch length of 3 mm. With careful designs, the total longitudinal broadband effective impedance is 11.4 mΩ, the total loss factor is 786.8 V/pC, and the total transverse kick factor is 20.2 kV/pC/m. From the budget we can conclude that the longitudinal and transverse broadband impedances are dominated by the resistive wall, flanges and bellows. The loss factor or parasitic power loss of the beam is mainly contributed by the resistive wall and the RF cavities.

Table 2: Impedance budget of the main contributors

Components	$Z_{\|}/n$, **mΩ**	k_y, **kV/pC/m**
Resistive wall	6.2	11.3
RF cavities	-1.0	0.3
Flanges	2.8	2.8
BPMs	0.1	0.3
Bellows	2.2	2.9
Pumping ports	0.02	0.6
IR	0.02	1.3
Electro-separators	0.2	0.2
Taper transitions	0.8	0.5
Total	11.4	20.2

IMPEDANCE DRIVEN INSTABILITIES

Microwave instability

The microwave instability will rarely induce beam losses, but may reduce the luminosity due to the deformed beam distribution and increase of the beam energy spread. The instability is simulated with the code Elegant [4, 5]. The dependences of bunch length and beam energy spread on the bunch charge are represented by the red curves in Fig. 5 and Fig. 6. The design bunch intensity is just above the instability threshold, and also turbulent distributions in longitudinal phase space are observed above the threshold, as shown in Fig.7.

Possible mitigations for this effect include impedance reduction and beam parameter optimization. Figures 5 and 6 show how the bunch length and beam energy spread evolve with bunch intensity for different impedance models. The purple and green lines show the behavior with only geometrical (GEO) and only resistive wall (RW) impedance, respectively. We can see that resistive wall impedance gives larger contribution to the bunch lengthening, while the geometrical impedance contributes more to the beam energy spread and instability threshold.

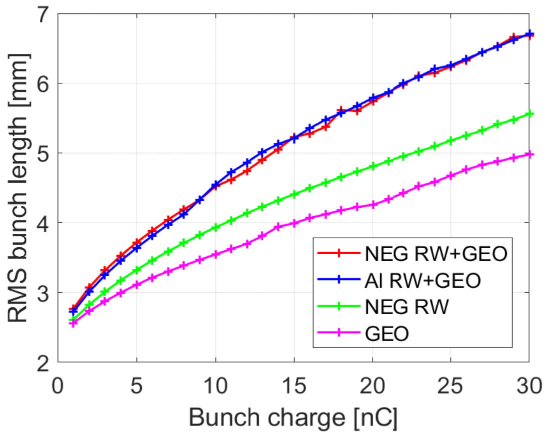

Figure 5: Dependence of bunch length on bunch charge with different impedance models.

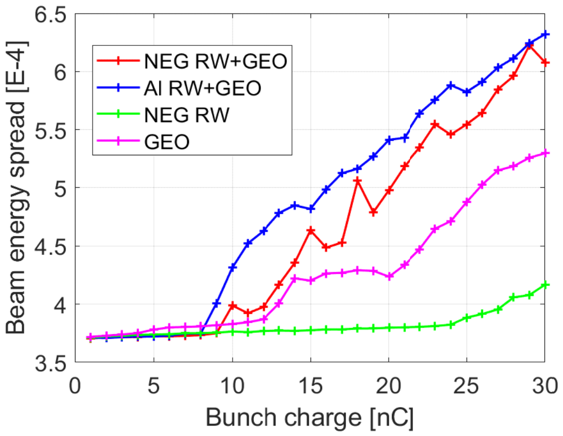

Figure 6: Dependence of beam energy spread on bunch charge with different impedance models.

Moreover, we also considered the case with aluminum (Al) beam pipe, as shown by the blue curves. The bunch lengthening is almost the same as for the NEG-coated beam pipe, but shows higher beam energy spread increase. By combining these results, we can get rough information of how much we can benefit from further impedance optimizations.

For the beam parameter optimization, a simple instruction is given by the Keil-Schnell criterion [6, 7]. We can get linear gain from increasing the momentum compaction, beam energy spread and bunch length. Meanwhile, beamstrahlung can also be beneficial.

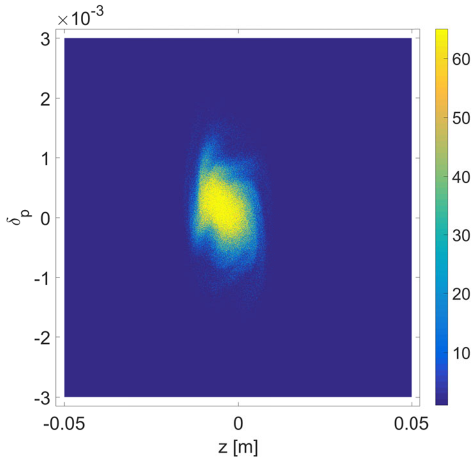

Figure 7: Longitudinal phase space distribution for a bunch charge of 10 nC. The color bar represents the number of macroparticles in each bin.

Transverse mode coupling instability

The threshold for the transverse mode coupling instability (TMCI) is estimated by the eigenmode analysis. The threshold current is comparable with the design value without considering bunch lengthening, as shown in Fig. 8. However, significant bunch lengthening can be induced by the impedance and beamstrahlung at high beam current. Accordingly, the transverse effective impedance will decrease due to its dependence on the bunch distribution. Therefore, larger safety margin is obtained when considering bunch lengthening effects, as shown in Fig. 9.

Transverse resistive wall instability

For the multi-bunch effects, coupled bunch instability can be driven by the resonance at zero frequency of the transverse resistive wall impedance. The most dangerous mode has a growth time of ~4.3 ms, which is about 12 turns. This is much faster than the radiation damping. Therefore, an effective bunch by bunch feedback system will be used to damp the instability. Meanwhile, a non-zero chromaticity can also help to shift the sampled impedance frequencies, and increase the beam current threshold.

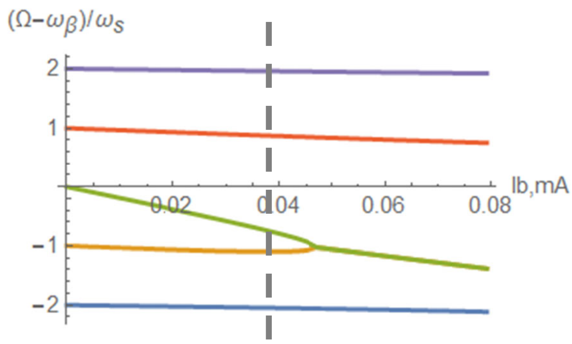

Figure 8: Head-tail mode frequency versus bunch intensity without bunch lengthening (the grey dashed line shows the design beam current).

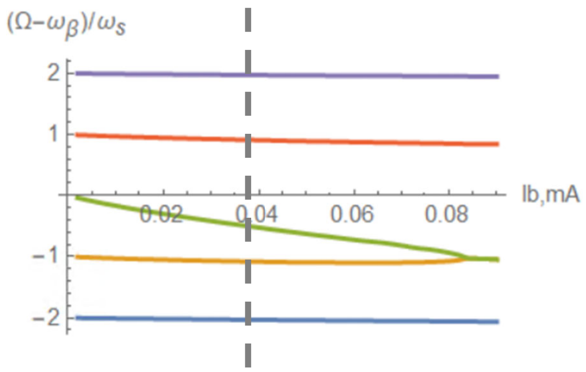

Figure 9: Head-tail mode frequency versus bunch intensity with bunch lengthening from impedance and beamstrahlung (the grey dashed line shows the design beam current).

Coupled bunch instabilities from RF HOMs

Another important contribution to the coupled bunch instability is the high order modes (HOMs) of the accelerating cavities. 120 2-cell superconducting RF cavities (650 MHz) will be used for Z mode. Calculations show that the transverse and longitudinal coupled bunch instability driven by the sum of the RF HOMs is faster than the radiation damping or even feedback damping.

However, considering the whole RF system, HOM frequency spread due to the actual tolerances of the cavity construction can further relax the instability. Figures 10 and 11 show how the total impedance evolves when we consider different HOM frequency spread. Taking into account a HOM frequency spread of larger than 0.5 MHz, the impedance is well below the threshold determined by feedback damping. Meanwhile, strategies to further damp the HOMs are under investigation.

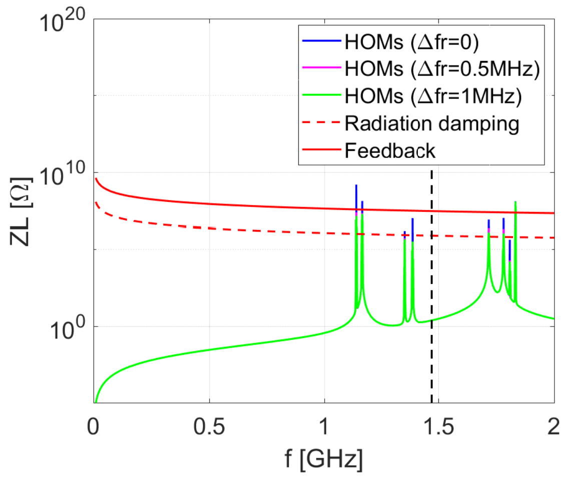

Figure 10: Impedance of the RF cavity monopole HOMs compared with the threshold determined by radiation damping and feedback damping of 5 turns.

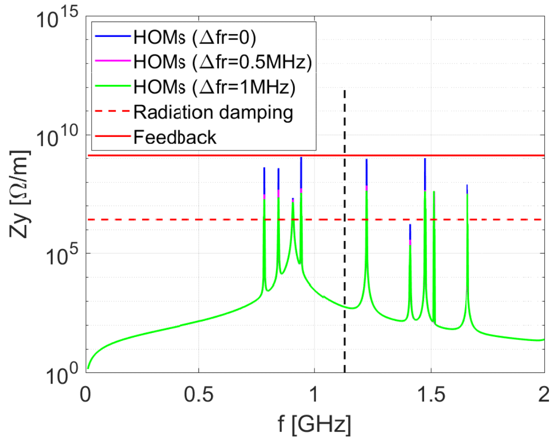

Figure 11: Impedance of the RF cavity dipole HOMs compared with the threshold determined by radiation damping and feedback damping of 5 turns.

FAST BEAM ION INSTABILITY

In the electron ring, beam ion instability can be severe due to high beam current and small emittance which are required to reach high luminosity. The beam ion interaction can cause emittance blow-up and a positive tune shift along the bunch train. To avoid these effects, low vacuum level is required along with a multi-train filling pattern. The build-up of the ions is calculated, as shown in Fig. 12. With the average ion density, we get the instability growth time of ~2 ms. An efficient transverse feedback is required to damp the instability. More detailed simulation studies are underway.

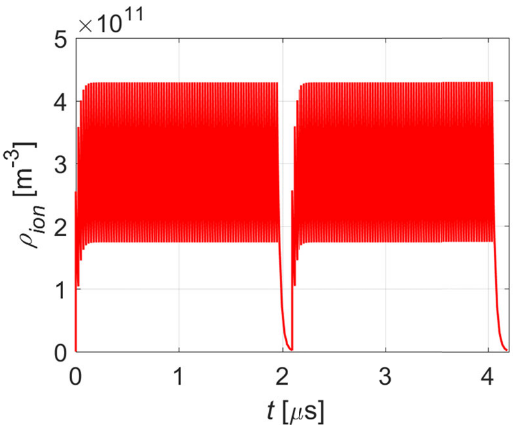

Figure 12: Build-up of the ions along the bunch train.

ELECTRON CLOUD EFFECTS

Electron cloud can degrade the beam through both single bunch and coupled bunch instabilities, which can induce beam size blow-up or beam losses. To mitigate this effect, multi-train filling pattern with certain bunch spacing is suggested. The electron cloud build-up in both dipole and drift region is simulated with different bunch spacing. The average electron cloud density is around 3.2×10^{10} m^{-3} with secondary electron yield (SEY) of 1.6 and bunch spacing of 25 ns. This is comparable to the threshold determined by the single bunch instability. The build-up of electron cloud will be further suppressed by the NEG coating, for which a lower SEY is expected.

INTERACTION WITH BEAM-BEAM

In conventional electron positron colliders, only the impedance-lengthened bunch is used in beam-beam simulations, instead of considering the impedance directly. This is not a problem since the longitudinal dynamics is not sensitive to beam-beam interaction. But it is different in high energy colliders since the bunch will also be lengthened during beam-beam interaction by beamstrahlung effect. It is very natural and more self-consistent to consider the longitudinal impedance directly in the beam-beam simulation [8].

By scanning the horizontal tune to see whether the transverse oscillation is stable with beam-beam interaction, it is found that the beam gets more unstable with impedance. One of the examples is demonstrated in Fig. 13. More studies show that reducing β_x in the interaction point is efficient to damp this effect. Further optimization of the beam parameters and impedance is required.

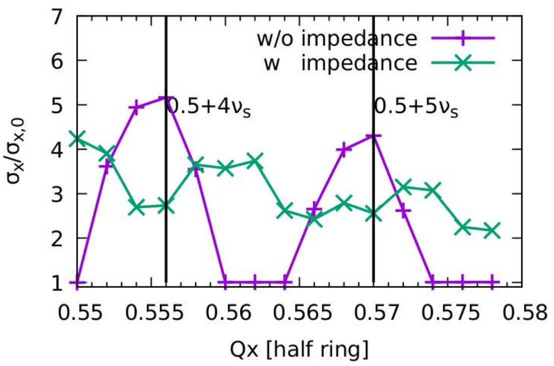

Figure 13: Horizontal beam size blow up in collision obtained by simulation with and without impedance.

CONCLUSION

The collective beam instabilities are potential restrictions in CEPC to achieve high luminosity performance. Different strategies used to mitigate these effects have been discussed. The single bunch instability is dominated by the microwave instability, which can induce longitudinal phase space distortions and couple with the beam-beam interaction. The beam parameters and impedance need to be further optimized to get larger stable region in tune. The coupled bunch instabilities from the resistive wall and RF HOMs need to be damped by efficient bunch by bunch feedback systems. The two stream instabilities require multi-train filling pattern with certain bunch spacing, along with feedback and vacuum conditioning.

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