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STUDIES AND MITIGATION OF COLLECTIVE EFFECTS IN FCC-ee*

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Abstract

In order to achieve a high luminosity in the future electron-positron circular collider (FCC-ee) very intense multi-bunch colliding beams should have nanometer scale transverse beam sizes at the collision points. For this purpose the emittances of the colliding beams are chosen to be very small, comparable to those of the modern synchrotron light sources, while the stored beam currents should be close to the best values achieved in the last generation of particle factories. In order to preserve beam quality and to avoid collider performance degradation, a careful study of the collective effects and techniques for their mitigation is required. The current status of these studies is discussed in the paper.

INTRODUCTION

The Future Circular Collider (FCC) is a challenging project that includes, in a single tunnel of about 100 km, both hadron [1] (FCC-hh) and electron-positron [2] (FCC-ee) colliders in the CERN area. The electron-positron machine will operate in four different stages corresponding to four energies, 45.6 , 80, 120 and 182.5 GeV, which will allow to study the properties of the Higgs, W and Z bosons, and top quark pair production thresholds with unprecedented precision.

In this paper we focus our study on the collective effects and instabilities of the lowest energy machine. The parameter list which we refer to, and shown in Table 1, has been updated with respect to that of the conceptual design report [2] (CDR). Therefore, previously evaluated impedances and related instabilities [3–6], as well as electron cloud and other effects [7–9], need to be reviewed.

The combined effect of beam-beam interaction and beam coupling impedance, which has a strong impact on the stability of the colliding beams, is particularly important for this machine. The beam-beam interaction alone has already given rise to new effects, such as beamstrahlung [10], coherent X-Z instability [11] and 3D flip-flop [12]. The beam dynamics becomes even more complex when also the wakefield effects are included [13–16]. Indeed, the combination of the beam-beam interaction with the longitudinal impedance reinforces the X-Z coherent beam-beam instability reducing and shifting the stable tune areas. In ref. [15], in order to find a stable tune area with the original CDR parameters, two mitigation techniques, that is the use of the harmonic cavities and an increase of the lattice momentum compaction factor, have been proposed. The updated parameter list has now a lattice with a momentum compaction factor twice that of the CDR. Additionally, another relevant change with respect to the CDR is the possibility of using 4 interaction points (4 IPs) instead of 2 IPs, as requested by particle physicists.

Table 1: Parameter List of the Z Machine with 4 IPs

Parameter	Value
Circumference (km)	91.174
Beam energy (GeV)	45.6
Bunch population (10^{11})	2.53
Bunches per beam	9600
RF frequency (MHz)	400
RF Voltage (GV)	0.12
Energy loss per turn (GeV)	0.0391
Longitudinal damping time (turns)	1167
Momentum compaction factor 10^{-6}	28.5
Horizontal tune/IP	55.563
Vertical tune/IP	55.600
Synchrotron tune	0.0370
Horizontal emittance (nm)	0.71
Verical emittance (pm)	1.42
Bunch length (mm) (SR/BS)*	4.37/14.5
Energy spread (%) (SR/BS)*	0.039/0.130
Piwinski angle (SR/BS)*	6.35/21.1
ξ_x/ξ_y	0.004/0.152
Horizontal β^* (m)	0.15
Vertical β^* (mm)	0.8
Luminosity/IP (10^{34}/cm^{2}s)	181

*SR: synchrotron radiation, BS: beamstrahlung

IMPEDANCE MODEL

Since FCC-ee is an evolving project, the machine impedance model is undergoing constant changes. Indeed, for several devices, as, for example, the collimators and injection kickers, a design has not been defined yet. Additionally, for some other devices, refined models for the determination of the coupling impedance are in progress. As a consequence, we report here the latest evaluation of some important contributions that already demonstrates how this machine can become critical due to collective effects.

The resistive wall represents the most important impedance source of FCC-ee [3]. For its evaluation we have considered a circular beam vacuum chamber with a radius of 35 mm and with two small lateral winglets necessary to place synchrotron radiation absorbers and to attach

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the localised vacuum pumps. The model of the beam pipe that we have used is shown in Fig. 1. It is made of copper with a thickness of 2 mm having a NEG coating of 150 nm for mitigating the electron cloud build-up in the positron machine and for pumping reasons in both rings. Behind the copper, we have a 6 mm of dielectric (air) and then an infinite layer of iron.

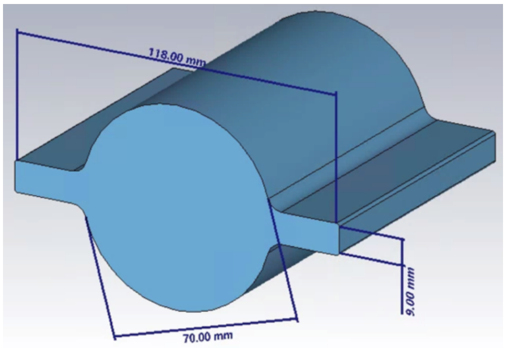

Figure 1: Beam pipe for the resistive wall impedance.

The second important contribution to the machine coupling impedance is given by the bellows. The latest realistic CAD model has been provided by the CERN vacuum group [17]. In order to avoid tapers which could contribute to the machine impedance, also the bellows have two lateral winglets like the vacuum chamber. Particular care has been dedicated to the study of the effect of RF shielding with small RF fingers used to ensure the electric contact between the two sides of the shielding. The contribution of the shielding is fundamental to suppress the low frequency resonances due to the bellows which otherwise would lead to a high impedance value. The complexity of the simulations due to the small mesh size, necessary to proper model the tiny fingers of the shielding, led to time consuming simulations and to the need of important computational resources.

The overall latest impedance model takes into account, in addition to the resistive wall and to 20000 bellows, also 4000 beam position monitors and the RF system formed by 52 single cell cavities and 2×13 tapers 500 mm long which guarantee a transition from 50 to 150 mm circular pipe inside each cryomodule. The total short range longitudinal and transverse wakefields of a 0.4 mm Gaussian bunch used as Green function in simulations, together with the different contributions, are shown in Figs. 2 and 3.

It is important to note that, except for the resistive wall and the bellows, all the other devices give a small contribution. The impedance of the collimation system is still under study.

SINGLE BUNCH COLLECTIVE EFFECTS

Beam dynamics simulations with the inclusion of the effects of the above described wakefields have been performed by means of PyHEADTAIL code [18], the results of which were preliminary compared with other tracking codes [19, 20].

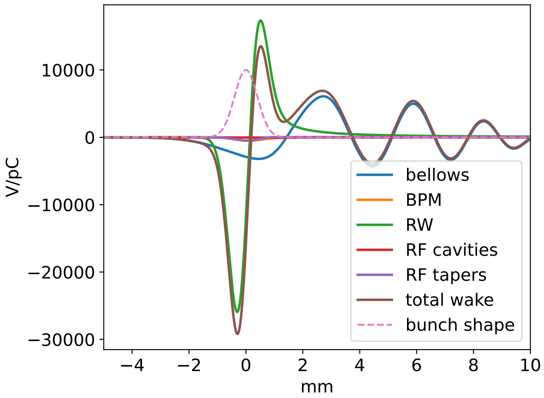

Figure 2: Longitudinal wakefield of 0.4 mm Gaussian bunch.

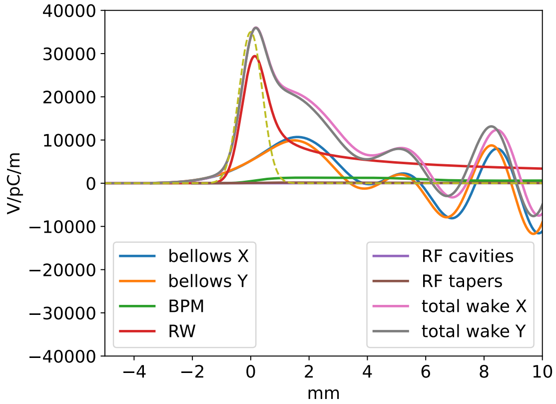

Figure 3: Transverse wakefield of a 0.4 mm Gaussian bunch.

The rms bunch length σ_z and energy spread σ_p as a function of the bunch population in presence of the longitudinal wakefield are shown in Fig. 4. The microwave instability threshold is around 2×10^{11}, about 20% lower than the nominal bunch intensity. We remind, however, that the microwave instability should be suppressed in collision due to higher

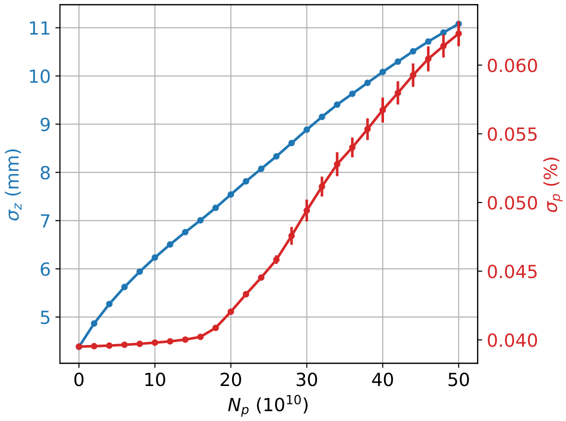

Figure 4: Bunch length σ_z (left) and energy spread σ_p (right) as a function of the bunch population.

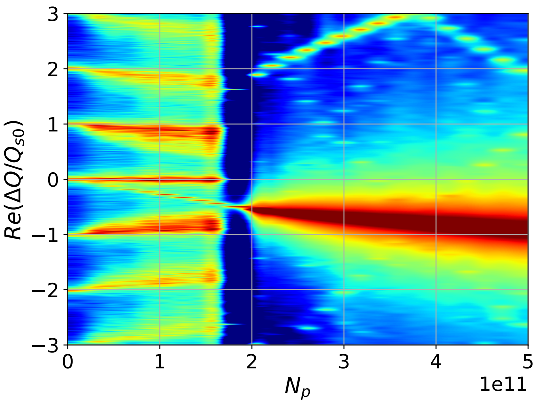

Figure 5: Real part of the tune shift of the first azimuthal transverse coherent oscillation modes normalised by the synchrotron tune Q_{s0} as a function of bunch population.

energy spread and the longer bunch. In any case this behaviour helps us to understand possible problems related to single bunch beam dynamics that may arise during the commissioning phase of the machine without beam-beam.

For what concerns the transverse beam dynamics, the most dangerous effect is the shift of the frequency of the coherent azimuthal mode '0' towards the mode '-1', giving rise to the so-called transverse mode coupling instability (TMCI) which, differently from the microwave, can result in beam losses. Coherent frequencies of the transverse modes are derived from PyHEADTAIL results by using the method described in [21]. In Fig. 5, we show the real part of the tune shift (with respect to the unperturbed betatron tune) of the first azimuthal transverse coherent oscillation modes, normalised by the unperturbed synchrotron tune Q_{s0} as a function of the bunch population. Simulations include the effect of the longitudinal wakefield which, through the synchrotron tune shift and spread, in particular of the '-1' mode, reduces the TMCI threshold up to about $N_p = 1.8 \times 10^{11}$. Similarly to what we observe in the longitudinal plane, we expect that also here the beamstrahlung will play a beneficial role. Additionally, the bunch-by-bunch transverse feedback, necessary to damp the transverse coupled bunch instability due to the resistive wall at low frequency, can give a useful contribution to reduce the shift of the '0' mode [22], thus increasing the TMCI threshold.

BEAM BEAM WITH 4 IPs

Due to a combination of different challenging beam parameters, such as very small emittances, small beta functions in the interaction points, a large Piwinski angle combined with the crab waist collision scheme [23, 24], and very high intensity, the beam-beam interaction gives rise to some important effects already mentioned in the introduction. Among them, one of the most critical for the machine performances is the coherent horizontal-longitudinal (X-Z) instability [11]. It is produced by the beam–beam interaction with large Piwinski angle and it is excited by the localised horizontal beam-beam force in the IPs. The instability manifests itself with a transverse beam size blow-up that can severely limit the stable tunes areas where the design luminosity can be achieved.

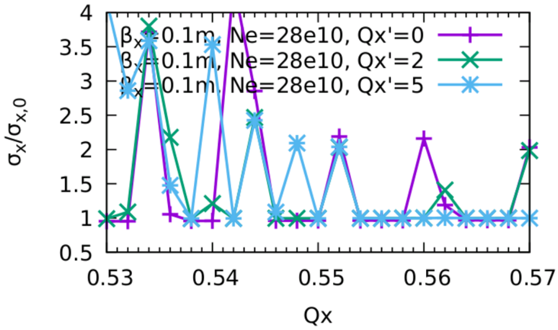

Figure 6: Normalised horizontal beam size $\sigma_x/\sigma_{x,0}$ as a function of the horizontal tune for a bunch population of $N_p = 2.8 \times 10^{11}$ at different chromaticities with $\beta_x^* = 10$ cm.

In previous studies [13–15, 25], the importance of the longitudinal impedance on the stability regions of the horizontal tune was highlighted. We have then performed simulations by including, at the same time, both effects: beam-beam interaction and longitudinal impedance. As a result, with the updated parameters, no stable region in the horizontal tune range $Q_x = 0.53 - 0.57$ was found. Also the chromaticity, in such conditions, didn't help to stabilise the beam. Since the X-Z instability threshold is inversely proportional to the horizontal betatron function at the interaction point, we reduced the β_x^* from 15 cm of table 1 to 10 cm and we managed to find two regions of stability around $Q_x = 0.56$, as shown in Fig. 6, even at beam intensities higher than the nominal one ($N_p = 2.8 \times 10^{11}$). Also a positive chromaticity, in this case, increases the stability of the machine [26].

CONCLUSIONS

In this paper we have reviewed the single bunch collective effects with the updated parameter list of FCC-ee. The microwave and TMCI instability thresholds due to the machine coupling impedance evaluated so far are both below the nominal intensity. However they are strongly influenced by the beamstrahlung which results to have an important mitigation effect. In turn, also beam-beam interaction and beamstrahlung are strongly influenced by the longitudinal coupling impedance and self consistent studies must take into account both effects at the same time.

We finally obtained a stable working point by reducing the horizontal betatron function at the IP. It is however important to underline that the update of the impedance model can change the stability conditions and it is necessary to look for additional tools that can be used to mitigate the collective effects for such a challenging machine.

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