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STUDIES OF FCC-ee SINGLE BUNCH INSTABILITIES WITH AN UPDATED IMPEDANCE MODEL*

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Abstract

The design of the FCC-ee collider is ongoing with the goal of optimizing beam parameters and developing various accelerator systems. As a result, the modelling of coupling impedance is continuously evolving to take into account the design of the collider vacuum chamber and hardware components. Concurrently, estimates of collective effects and instabilities are being continually updated and refined. This paper presents the current FCC-ee impedance model and reports the findings of the single-bunch instability studies. Additionally, some potential mitigation techniques for these instabilities are discussed.

INTRODUCTION

The Future Circular Collider (FCC) is an ambitious project that will house, in a single tunnel, both hadron [1] (FCC-hh) and electron-positron [2] (FCC-ee) colliders in the CERN area. The electron-positron machine foresees four different operation stages with energies of 45.6, 80, 120 and 182.5 GeV. They will allow studying the properties of the Higgs, W and Z bosons, and top quark pair production thresholds respectively.

Since the design of this machine is still in progress, also the coupling impedance budget is continuously evolving in parallel with the updates of the vacuum chamber components. Correspondingly, also the collective effects and instability thresholds need constant revision.

In this paper, we focus our study on the single beam impedance-induced instabilities related to the lowest energy machine, which is most challenging from the collective effects point of view. In particular, for the beam dynamics simulations, we use the parameter list discussed in [3] and present an update of previously evaluated impedances and related instabilities [4–9].

IMPEDANCE MODEL

The most important impedance contribution evaluated so far comes from the resistive walls (RW) of the vacuum chamber. The beam pipe, having a radius of 35 mm, is made of copper coated with a 150 nm thin layer of NEG used for pumping purposes and electron cloud suppression. Two lateral winglets are foreseen [8] for placing synchrotron radiation absorbers. It has been shown that these winglets give a negligible contribution to the impedance. In particular, as one can see in Fig. 1, for the frequency range of interest the longitudinal RW impedance calculated by the 2D electromagnetic solver VACI [10] for the geometry with the winglets practically coincides with that of the round beam pipe obtained by using IW2D code [11].

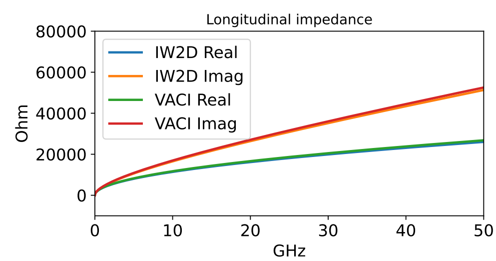

Figure 1: Resistive wall longitudinal impedance for FCC-ee.

The collimation system is another important impedance source. For FCC-ee two types of collimators are foreseen: the beam halo collimators, to be used to limit detector backgrounds and to protect sensible machine equipment [12], and the synchrotron radiation collimators and masks, to intercept photons upstream the interaction points. Due to the high stored beam energy a dedicated two-stage halo collimation system will be used with the collimators made of materials with low atomic numbers (Molybdenum, Molybdenum-Graphite). The geometric dimensions of the collimators and the beta function at their locations are summarized in Table 1 [13], and a model for the impedance evaluation is shown in Fig. 2.

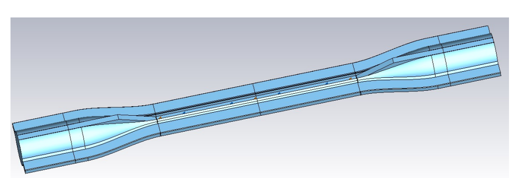

Figure 2: Betatron and off-momentum collimator model.

From the table, we can notice their nonnegligible length and, in particular for the three vertical collimators, a small half gap of about 2 mm, which makes their transverse dipolar resistive wall impedance contribution much higher than that of the other collimators. In addition, we have also to consider the tapering necessary for the transition from 35 mm to the

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Table 1: Halo Collimators

name	l (m)	$g/2$ (mm)	β_x (m)	β_y (m)
tcp.h.b1	0.4	5.5	352.58	113.05
tcp.v.b1	0.4	2.3	147.03	906.28
tcs.h1.b1	0.3	4.2	144.37	936.12
tcs.v1.b1	0.3	2.0	353.43	509.32
tcs.h2.b1	0.3	6.0	295.62	1419.38
tcs.v2.b1	0.3	2.1	494.24	554.06
tcp.hp.b1	0.4	5.8	55.47	995.31
tcs.hp1.b1	0.3	16.0	373.99	377.28
tcs.hp2.b1	0.3	12.0	184.97	953.23

In the collimators' name, 'p' stands for primary, 's' for secondary, 'v' for vertical, and 'h' for horizontal. Additionally, $l \rightarrow$ length, $g \rightarrow$ full gap.

small gap which gives an additional geometric contribution that still needs to be better investigated.

Bellows represent another important source of impedance. Differently from [3], their number is reduced to about 9000 since they are now supposed to be 12 m apart in the dipole arcs with respect to the previous 8 m.

In Fig. 3 we show the updated transverse dipolar wake potential of a 0.4 mm Gaussian bunch used as a pseudo-Green function for beam dynamics studies. For the collimators, only the resistive wall contribution has been included so far.

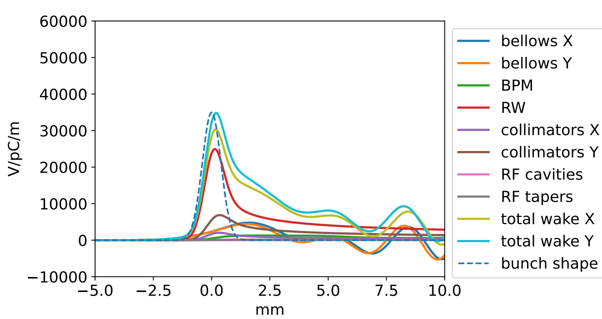

Figure 3: Transverse dipolar wake potential of 0.4 mm Gaussian bunch.

As a comment on this plot, we have to remind that the collimators' contribution is going to increase due to the geometrical wake. Additionally, very recently, in order to reduce the quadrupoles and sextupoles power request, a lower beam pipe radius (from $b = 35$ mm to 30 mm) was suggested. Since the transverse RW impedance is proportional to b^{-3}, we expect an increase of this contribution of about 60%. But also all the devices (except the collimators) will increase their impedance, even if not with the same scaling factor.

LONGITUDINAL EFFECTS

Below the microwave instability threshold, longitudinal wakefields result in bunch lengthening and bunch shape distortion. Above the instability threshold also the energy spread starts growing and the internal bunch motion becomes more turbulent. The internal bunch oscillations can be harmful to reach the nominal luminosity and, besides, this effect can lead to the detector background increase and injection saturation, see [14] for example. However, in the FCC-ee the longitudinal dynamics is strongly affected by the beam-beam interaction with a large Piwinski angle and beamstrahlung [15]. The bunch length and the energy spread increase in collision due to beamstrahlung thus helping to suppress also the microwave instability.

Longitudinal beam dynamics simulations have been performed with PyHEADTAIL code [16] that was compared with other tracking codes [17, 18], also for the FCC-ee case, giving a very good agreement.

In Figs. 4 the bunch length (top) and the energy spread (bottom) are represented as a function of the bunch population. As it is seen, the inclusion of the beamstrahlung arising in collision changes drastically the beam dynamics results. In the single beam mode, the bunch length at the nominal intensity (indicated by the black dashed line) is almost doubled with respect to the natural bunch length, while the small energy spread increase is a sign of the beginning of microwave instability. So in this case the bunch length increase is mainly produced by the potential well distortion.

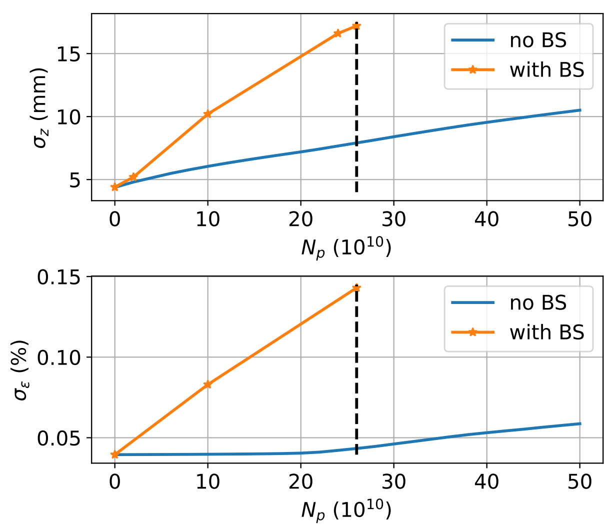

Figure 4: Bunch length (top) and energy spread (bottom) with and without the beamstrahlung effect as a function of the bunch population.

On other hand, in collision, a large increase in the longitudinal emittance is observed. The bunch lengthening and the energy spread growth are predominantly defined by the collision beamstrahlung. The effect of the wakefields is less pronounced in such a case. Nevertheless, both regimes are important for collider operations. While the collision mode is the most important for the luminosity production runs, the single beam mode is to be considered for the machine commissioning and tuning. Here we must underline that the wakefields play anyway a substantial role for the beam-beam interaction, reducing the width of the stable tune regions and shifting them on the tune diagram with the bunch intensity increase thus making stable collider operation challenging [19].

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The interplay of the beam-beam effects with the wakefields is discussed in another paper of these proceedings [20].

TRANSVERSE EFFECTS

The main effect of the transverse wakefield on the single bunch dynamics is the excitation of the so-called transverse mode coupling instability (TMCI) [21]. Under certain conditions, the frequencies of some coherent transverse oscillation modes of a bunch can shift and couple together. In particular, for FCC-ee, the '0' mode shifts towards the '-1' one. When they couple together, the instability occurs with consequent loss of the beam (or a part thereof).

The coherent frequencies of the lowest order modes can be obtained from the results of PyHEADTAIL with a proper analysis described in [22]. We have additionally found that for FCC-ee the TMCI threshold depends on the longitudinal wakefield [23]. In Fig. 5 the real part of the tune shift of the first azimuthal transverse oscillation modes normalized by the synchrotron tune Q_{s0} is shown as a function of bunch population. As it can be seen, the instability threshold is about 1.6×10^{11}, that is below the nominal bunch intensity.

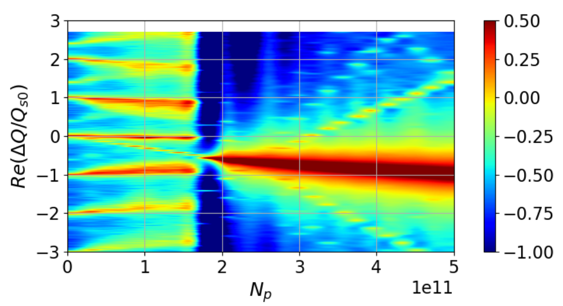

Figure 5: Real part of the tune shift of the first azimuthal transverse coherent oscillation modes normalised by the synchrotron tune Q_{s0} as a function of bunch population.

In addition to the single bunch TMCI, a coupled bunch instability driven by the real part of the resistive wall impedance at low frequency can be excited. Its study can be performed by considering the motion of the entire beam (not of the single bunch) as a sum of coherent coupled bunch oscillation modes. The instability occurs when the frequencies of these modes are negative and they couple with the real part of the impedance, which becomes higher approaching to zero frequency. Figure 6 shows the beam spectrum of some coupled bunch modes with a fractional part of the tune equal to $\nu_\beta = 0.4$ and the real part of machine impedance at low frequency.

The most unstable mode has a growth rate of a few turns. This instability depends on the fractional part of the betatron tune and on cromaticity, and it can be mitigated by a bunch-by-bunch feedback system, as that used in other circular accelerators (DAΦNE, SuperKEKB, ...). Such feedback, in combination with the longitudinal wakefield, has also a mitigating effect on the TMCI [24]. Indeed, with the feedback on, the spectrum of the first coherent single-bunch modes is shown in Fig. 7. We can see that the beam is now stable up to an intensity of 4.4×10^{11}, above which we do not have the mode coupling as in Fig. 5, but another type of instability of the single mode '-1' [25].

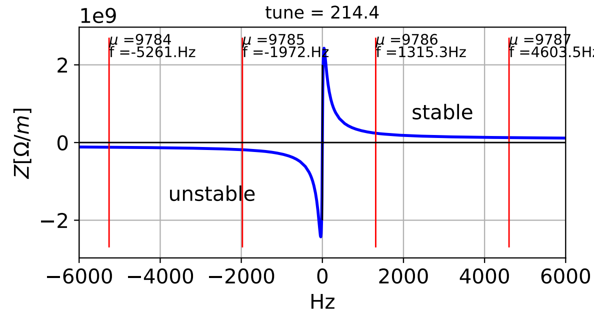

Figure 6: Coupled bunch spectrum and real part of the resistive wall impedance as a function of frequency.

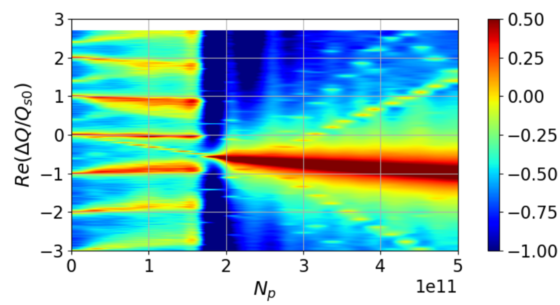

Figure 7: Real part of the tune shift of the first azimuthal transverse coherent oscillation modes normalised by the synchrotron tune Q_{s0} as a function of bunch population.

With the reduction of the vacuum chamber radius to 30 mm, the intensity threshold is about 16% lower. However, we must observe that the results related to the transverse wakefield are valid in the single beam regime, without the beamstrahlung effect. For self-consistent results in collision, we have also to include the beam-beam effects. This contribution is discussed in [20].

CONCLUSIONS

This paper provides a review of the single bunch collective effects studied by using the updated impedance model and the updated FCC-ee parameter list. A first model of the collimation system has been included in the impedance contribution. Both the microwave and TMCI instability thresholds due to the machine coupling impedance have been evaluated and found to be below the nominal intensity. However, the presence of beam collision beamstrahlung has been shown to have an important mitigation effect on the longitudinal plane, while a bunch-by-bunch feedback system, necessary to damp the transverse coupled bunch instabilities, counteracts also the TMCI.

The regime of colliding beams, including the beam-beam that has a strong influence on collective effects, will be discussed in a dedicated paper in these proceedings.

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