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TRANSVERSE AND LONGITUDINAL SINGLE BUNCH INSTABILITIES IN FCC-ee

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Abstract

Improving the accuracy of the impedance model of an accelerator is important for keeping beam instabilities and power loss under control. Here, by means of the PyHEADTAIL tracking code, we first review the longitudinal microwave instability threshold for FCC-ee by taking into account the longitudinal impedance model evaluated so far. Moreover, we present the results of beam dynamics simulations, including both the longitudinal and transverse wakefields due to the resistive wall, in order to evaluate the influence of the bunch length on the transverse mode coupling instability. The results of the transverse beam dynamics are also compared with the Vlasov solver DELPHI.

INTRODUCTION

To prepare for the era after the High-Luminosity Large Hadron Collider project, and following the 'European Strategy Update' 2020, the feasibility study for a Future Circular Collider (FCC) has been launched. FCC has a circumference of about 100 km. Its first stage is foreseen to be an electron-positron collider (FCC-ee) with center of mass collision energies ranging from 88 GeV to 365 GeV [1].

In a particle accelerator like the FCC-ee, the impact of collective effects should be evaluated, produced by self-induced electromagnetic fields (wakefields), which perturb the beam dynamics and could represent one of the main limitations to the machine operation and performance. Wakefields can produce instabilities in both longitudinal and transverse planes.

In particular, in this paper, we focus on the effects generated by the interaction of the beam with some important sources of wakefields for the FCC-ee main ring at the Z pole. Our study will consider single beam instabilities, and in particular the microwave instability and the Transverse Mode Coupling Instability (TMCI) in the longitudinal and transverse planes respectively.

The longitudinal instability manifests itself with a sudden increase of the energy spread and bunch length as a function of bunch intensity. In this regime of microwave instability, even if the bunch is not lost, it could oscillate reducing the machine performance. Moreover, the bunch shape could be strongly distorted with respect to the original Gaussian shape [2].

The TMCI [3], also called the strong head-tail instability, could also represent a serious limitation for the machine operation: above a certain intensity threshold, the particles motion grows exponentially and, differently from the microwave instability, the bunch could be lost.

Our paper is organized as follows. Firstly, the impedance of some machine devices has been updated with respect to a previous work [4]. We have then studied the single bunch longitudinal dynamics by means of the tracking code PyHEADTAIL [5], by taking into account the updated wakefield, and we have evaluated the new microwave instability threshold. Finally, transverse beam dynamics simulations, taking into account only the finite resistivity of the beam pipe, the so-called resistive wall (RW), which is however the most important source of machine impedance, have been performed in order to study the TMCI effect. Simulations have also been compared with the Vlasov solver DELPHI [6]. The study has been then extended to include the effect of the longitudinal RW wakefield to understand the interplay between the two planes.

WAKEFIELDS AND IMPEDANCES

Since RW represents the main source of impedance for FCC-ee, particular care has been taken to properly simulate the vacuum chamber. The beam pipe model used for the evaluation of coupling impedance and wakefield is assumed to be circular with a 35 mm radius, neglecting the small perturbations introduced by the lateral winglets for synchrotron radiation absorption [4]. The walls are supposed to be made of four layers: a first thin layer of Non-Evaporable Getter (NEG) coating 100 nm thick, a substrate of copper with a thickness of 2 mm, followed by a 6 mm of dielectric (air) and, finally, the magnet chamber modelled as an outer layer of iron with resistivity $\rho = 10^{-7}\,\Omega$m and infinite thickness [7]. By using the code IW2D [8], we calculated the coupling impedance and the wakefield, taking into account this multilayer system.

For the other impedance sources evaluated so far, that is the bellows, the beam position monitors (BPMs), the RF cavity system and tapers connecting each cryomodule (having 4 RF single cell cavities) to a circular beam pipe, they have been evaluated by using CST Microwave Studio [9]. CST gives, as result, the wake potential of a Gaussian bunch. On the other hand, IW2D gives in output the wakefield of a point charge, the so-called Green function. In order to use all the wakefields in PyHEADTAIL, for consistency, we have evaluated the wake potential of a 0.4 mm Gaussian bunch (also for IW2D, by a convolution integral) and used

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it as input wake in the simulation code. As a check of this procedure, we have evaluated the wake potential of 0.4 mm and 3.5 mm Gaussian bunches (this last one corresponding to the nominal bunch length without collision) directly with CST code, and then used the wake potential of the 0.4 mm bunch as Green function to check if we could reconstruct that of 3.5 mm. As an example, the results for a single bellow are shown in Fig. 1.

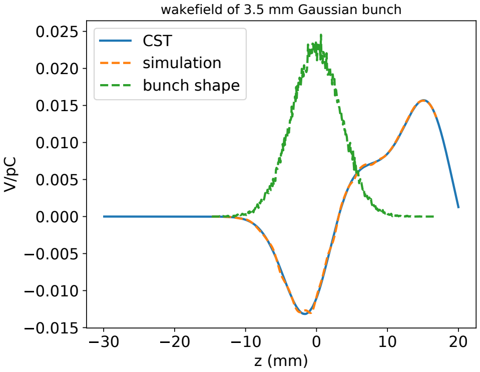

Figure 1: Single bellow wake potential of 3.5 mm Gaussian bunch obtained directly by CST (blue curve) and with the convolution by using the wake potential of a 0.4 mm Gaussian bunch (orange curve).

For the evaluation of the total impedance, we have updated the model of ref. [4]. In particular, the number of bellows has been updated: a more careful assessment of all ring dipole and quadrupole/sextupole arcs indicates that a realistic number would be around 12000-13000. In our simulations, to be conservative, we considered 20000 bellows.

The wake potential of a 3.5 mm Gaussian bunch for all the elements evaluated so far is shown in Fig. 2.

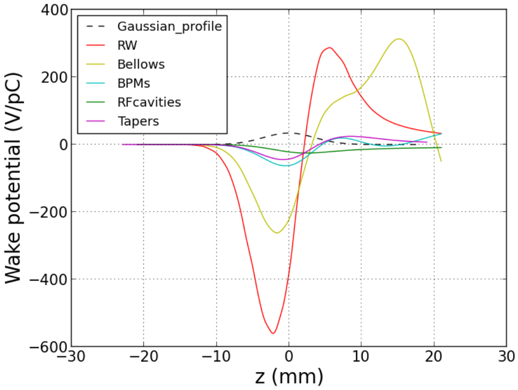

Figure 2: Longitudinal wake potentials of some machine elements evaluated so far for a Gaussian bunch with a nominal bunch length of 3.5 mm.

FCC-ee colliding beams are strongly influenced by the beamstrahlung effect, which increases the bunch length from a nominal value of 3.5 mm to 12.1 mm. As a consequence, for the evaluation of the beam power losses, we have used this second value as nominal bunch length, and Table 1 presents the results. We can see that the major contribution to the total losses is due to the RW, with a loss factor at nominal intensity of 33.1 V/pC.

Table 1: Loss Factor and Power Loss Contribution of Some FCC-ee Components at Bunch Length of 12.1 mm, in the Lowest Energy Case of 45.6 GeV

Component	**Number**	$\mathbf{K_{loss}\,[V/pC]}$	$\mathbf{P_{loss}\,[MW]}$
Resistive Wall	97.75 km	33.1	1.21
RF cavities	52	8.76	0.334
BPMs	4000	4.81	0.180
Bellows	20000	23.95	0.880
RF double tapers	13	2.33	0.088

We must underline that FCC-ee is a new project and the machine impedance model is still been refined. In fact, for several devices, such as the collimation system, a design has not been defined yet. As a consequence, the collective effects discussed in the following sections and due to the wakefields presented here can become more critical.

LONGITUDINAL DYNAMICS

As we mentioned in the introduction, above a given intensity threshold, the energy spread starts to increase in what is known as microwave instability regime, characterised by a turbulent behaviour of the longitudinal phase space. With the longitudinal wakefield discussed in the previous section, PyHEADTAIL simulations give the bunch length and energy spread as a function of the intensity shown in Fig. 3. In the figure, we represent the behaviour for both the initial nominal rms bunch lengths of 3.5 mm and for 12.1 mm, that is without and with beamstrahlung.

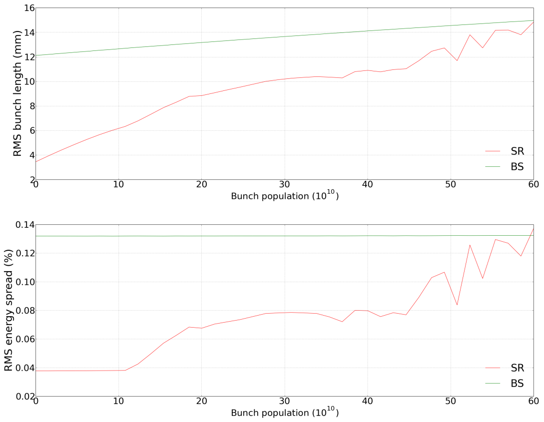

Figure 3: Bunch length (top) and RMS energy spread (down) as a function of bunch population in the case with (BS) and without (SR) beamstrahlung.

We can see that without collision, at the nominal intensity of 1.7 × 10^{11}, we are in the microwave instability regime, with a bunch length increasing by a factor of about 2.4 with respect to the nominal one, and an energy spread of a factor of about 1.6. On the other hand, we can also see that the effect of the wakefield is much weaker for the initial bunch length of 12.1 mm. Indeed in this case the bunch length hardly changes as a function of intensity, and the energy spread remains constant. As a consequence, we can conclude that in collision the single bunch longitudinal dynamics with the wakefield model evaluated so far is stable in case we take into account the beamstrahlung effect.

TRANSVERSE DYNAMICS

In the transverse plane, when increasing the bunch intensity, due to the wakefield, there is a shift of the coherent betatron frequencies of the intrabunch modes. The TMCI occurs when the frequencies of two neighbouring coherent oscillation modes merge together [7]. Unlike the microwave instability, above the transverse instability threshold the bunch is lost and this makes the TMCI very dangerous for the beam. In this case, for the simulations, we have considered so far only the RW wakefield given by IW2D. In addition to simulations with the tracking code, the TMCI threshold has been also evaluated with the analytic Vlasov solver DELPHI [6], which solves the Sacherer integral equation [3] by using a decomposition of the longitudinal distribution in coherent oscillation modes, and it finds the frequency of these modes at different bunch intensity.

Following the same idea of the longitudinal plane, also in this case, for PyHEADTAIL, we have used the RW wakefield of a short bunch with a length of 0.4 mm as Green function. DELPHI, on the other hand, uses the impedance in frequency domain given directly by IW2D.

Both approaches are important for estimating the coherent beam stability limits, and their results are shown, as comparison, in Fig. 4, where we reported the real part of the coherent tune shift with respect to the betatron tune ΔQ of the first azimuthal modes, divided by the unperturbed synchrotron tune Q_{s0}, as a function of the bunch population N_p.

At low intensity, we observe the coherent frequencies at multiples of the unperturbed synchrotron frequency. When the intensity increases, there is a shift, in particular of the frequency of the 0 mode down to -1. No instability is observed in this case up to a bunch population of $N_p = 2.8 \times 10^{11}$.

The green dots represent the DELPHI results, which well fit with the PyHEADTAIL simulations for which the colours are proportional to the amplitude of the frequency spectrum of the various moments of the distribution [10]. Red corresponds to the largest amplitude, blue to the lack of signal. We can conclude that there is an excellent agreement between the two methods up to the instability threshold.

Since the TMCI threshold strongly depends on the bunch length, which, in turn, is affected by the longitudinal dynamics, we have also performed simulations with PyHEADTAIL by taking into account, at the same time, both the longitudinal and transverse RW wakefield.

The results are shown in Fig. 5, where we can see that even at low intensities, several frequency lines start to appear for each azimuthal mode. These can be interpreted as the product of different radial modes of the same azimuthal family, and the TMCI threshold is reduced to about $N_p = 1.7 \times 10^{11}$. This reduction of the TMCI threshold is supposed to be produced by the lower coherent synchrotron frequency and by its spread due to the longitudinal wakefield.

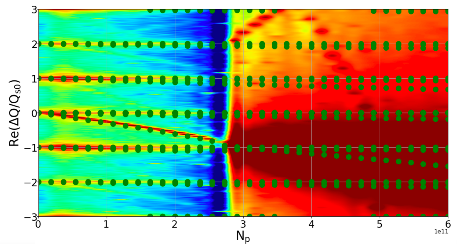

Figure 4: Real part of the coherent tune shift as a function of intensity, comparing PyHEADTAIL and DELPHI for the transverse resistive wall wakefield.

This important result related to the reduction of the TMCI threshold due to the longitudinal wake requires future thorough investigations, as well as possible mitigation solutions.

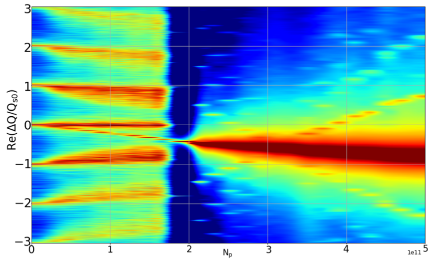

Figure 5: Real part of the tune shift as a function of intensity, considering the combined effect of longitudinal and transverse wakefields for the resistive wall case.

CONCLUSIONS

We carried out studies of the longitudinal and transverse single bunch collective effects for FCC-ee main ring at the Z pole, by considering an updated model of the wakefield. In particular the longitudinal beam dynamics at the nominal intensity is stable only under collisions, thanks to the beamstrahlung effect. Otherwise, due to the longitudinal wakefields, we are in the microwave instability regime. In the transverse plane, the TMCI threshold, that has been evaluated so far only accounting for the RW wakefield, is strongly reduced by including the effect of the longitudinal collective effects. It is important to underline that the machine impedance model needs to be further extended to ultimately include all FCC-ee machine devices, while examining any consequent changes in instability thresholds and beam dynamics.

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