PROCEEDINGS OF SCIENCE

FCC-ee Collective Effects and Their Mitigation*

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The high luminosity foreseen in the future electron-positron circular collider (FCC-ee) necessitates very intense multi-bunch colliding beams with very small transverse beam sizes at the collision points. This requires transverse beam emittances comparable to those of modern synchrotron light sources. At the same time, the stored beam currents should be close to the best values achieved in the last generation of particle factories. This combination of demanding factors poses a major challenge, namely preserving a high beam quality, while, at the same time, avoiding machine performance degradation. In consequence, a careful study of the collective effects and identification of stabilizing mechanisms are required to mitigate the foreseen instabilities. In this contribution, we discuss the current status of these studies.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

*Speaker

PoS(ICHEP2022)046

PoS(ICHEP2022)046

1. Introduction

Following the 2020 European Strategy Update, a feasibility study for a future circular collider (FCC) has been launched. The first stage of the FCC is an electron-positron collider (FCC-ee [1]) with centre-of-mass collision energies ranging from 91.2 to 365 GeV. According to the last updated parameter list, presented in Table 1, the FCC has a circumference of about 91 km.

Table 1: Baseline beam parameters for the FCC-ee in different modes of operation. The acronyms “SR” and “BS” signify synchrotron radiation and beamstrahlung, respectively.

Layout	PA31-1.0			
	Z	WW	ZH	$t\hat{t}$
Circumference (km)	91.174117 km			
Beam energy (GeV)	45.6	80	120	182.5
Bunch population (10^{11})	2.53	2.91	2.04	2.64
Bunches per beam	9600	880	248	36
RF frequency (MHz)	400			400/800
RF Voltage (GV)	0.12	1.0	2.08	4.0/7.25
Energy loss per turn (GeV)	0.0391	.37	1.869	10.0
Longitudinal damping time (turns)	1167	217	64.5	18.5
Momentum compaction factor 10^{-6}	28.5		7.33	
Horizontal tune/IP	55.563		100.565	
Vertical tune/IP	55.600		98.595	
Synchrotron tune	0.0370	0.0801	0.0328	0.0826
Horizontal emittance (nm)	0.71	2.17	0.64	1.49
Verical emittance (pm)	1.42	4.34	1.29	2.98
IP number	4			
Nominal bunch length (mm) (SR/BS)*	4.37/14.5	3.55/8.01	3.34/6.0	2.02/2.95
Nominal energy spread (%) (SR/BS)*	0.039/0.130	0.069/0.154	0.103/0.185	0.157/0.229
Piwinski angle (SR/BS)*	6.35/21.1	2.56/5.78	3.62/6.50	0.79/1.15
ξ_x/ξ_y	0.004/0.152	0.011/0.125	0.014/0.131	0.096/0.151
Horizontal β^* (m)	0.15	0.2	0.3	1.0
Vertical β^* (mm)	0.8	1.0	1.0	1.6
Luminosity/IP (10^{34}/cm^{2}s)	181	17.4	7.8	1.25

*SR: syncrotron radiation, BS: beamstrahlung

For a particle accelerator like FCC-ee, the impact of collective effects needs to be evaluated. Such effects are generated by self-induced electromagnetic fields (wakefields), which perturb the beam dynamics, and are likely to represent one of the main limitations to machine operation and performance. Wakefields are responsible for instabilities in both the longitudinal and transverse planes.

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 energy. This lowest machine energy is supposed to be the most critical with regard to collective effects.

Our study focuses on single beam instabilities, in particular on the microwave instability (MI) and on the transverse mode coupling instability (TMCI), which occur in the longitudinal and transverse planes, respectively [2]. The longitudinal MI manifests itself through a sudden increase of the energy spread and bunch length above a given intensity threshold. In this regime, even if the bunch is not lost, its longitudinal shape could oscillate, thereby reducing the machine performance. On the contrary, with TMCI, the transverse oscillations increase exponentially making the bunch to hit the pipe walls.

Additionally, we will discuss possible mitigation for these instabilities.

2. Wakefield and impedance

The beam pipe model used for the evaluation of the resistive wall (RW) coupling impedance and the associated wakefield, which results to be the most important impedance source of the machine so far, is taken to be a circular tube with a radius of 35 mm made up of four different layers. For our

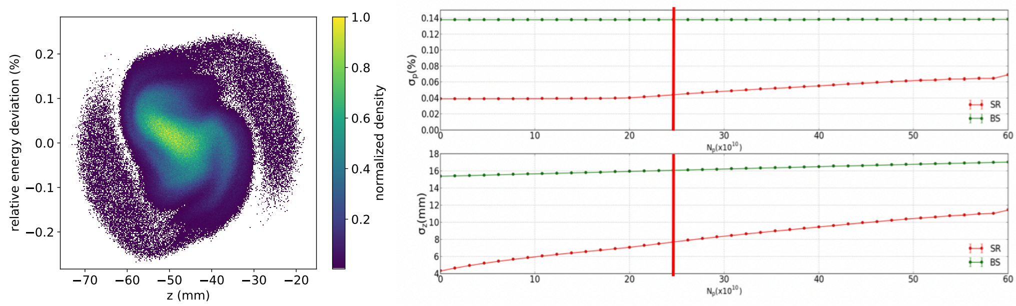

Figure 1: Left-hand side: longitudinal phase space at nominal intensity. Right-hand side: bunch length (bottom) and RMS energy spread (top) as a function of bunch population under the influence of the longitudinal RW impedance, for the case with (BS) and without (SR) beamstrahlung. Here, the effect of BS is considered to be constant, independent of the longitudinal impedance.

simulations of collective effects, we assume a NEG film thickness of 150 nm, that constitutes a good compromise between minimum thickness for a small impedance and the requirements coming from the vacuum and electron cloud effects. The NEG film is deposited on a 2 mm thick copper beam pipe. On the outer side, first a layer of air and, finally, thick iron follow, to model the influence of the machine magnets [3, 4]. Using the code IW2D [5], we calculate the RW coupling impedance and its associated beam wakefield, taking into account this multilayer system [6]. We also approximate the effect of small perturbations introduced by the lateral winglets for synchrotron radiation absorption, by multiplying the RW impedance and wakefield obtained for the circular pipe by a factor of 1.1, a value obtained from CST Microwave Studio [7] simulations.

The same CST code was also used to evaluate a number of other impedance sources, namely the bellows, the beam position monitors (BPMs), the RF cavity system and tapers connecting each cryomodule (housing 4 RF single cell cavities) to a circular beam pipe. In Ref. [8] the method to calculate the wake potential for our analysis and the relevant results are presented in detail. The machine impedance modelling is still in progress.

3. Microwave instability

Above a certain intensity threshold, the energy spread starts to increase, in what is known as the MI regime, which is characterized by a turbulent behavior of the longitudinal phase space. With the longitudinal wakefield as input, PyHEADTAIL [9, 10] simulations yield the bunch length and energy spread as a function of the intensity, as are shown in Fig.1, right-hand side. Indeed, in the same figure, on the left-hand side, we can see the longitudinal phase space distribution at nominal bunch intensity strongly distorted due to the turbulent behavious of the bunch.

Since the nominal bunch population is $25{\times}10^{10}$, we are in the MI regime if we do not take into account the effect of the collision (single beam red curves). If we also include the beamstrahlung effect for colliding beams (green curves), the energy spread is much larger and it remains constant, and the bunch length is only slightly modified by the impedance, due to potential wall distortion. Hence, in this latter case, no MI is observed.

From these results we can conclude that the beamstrahlung helps to mitigate the MI, but these simulations are not fully self-consistent, since the beamstrahlung also depends on the bunch length, while in this study we considered the beamstrahlung and the collective effects due to the wakefields independently of each other. This self-consistency aspect has been investigated more closely in a study of beam-beam interactions [11, 12].

4. TMCI

The TMCI can affect high intensity bunches in circular accelerators. This single bunch effect occurs if two transverse coherent oscillation modes couple with each other [13]. The effect can be reproduced and visualized with the code PyHEADTAIL [14]. When increasing the bunch intensity, due to the wakefield, the coherent betatron frequencies of the intrabunch modes are shifting. The TMCI occurs above a given bunch intensity when the frequencies of two neighbouring coherent oscillation modes merge together and the particles' motion grows exponentially.

Figure 2, left-hand side, shows the results of simulations with only the transverse wakefield. Above a certain threshold, at an intensity of about 21×10^{10} particles per bunch, a coupling between the modes 0 and -1 is clearly seen. The inclusion of the longitudinal wakefield effect further reduces the TMCI instability threshold, as is shown in the right-hand side of the figure. The

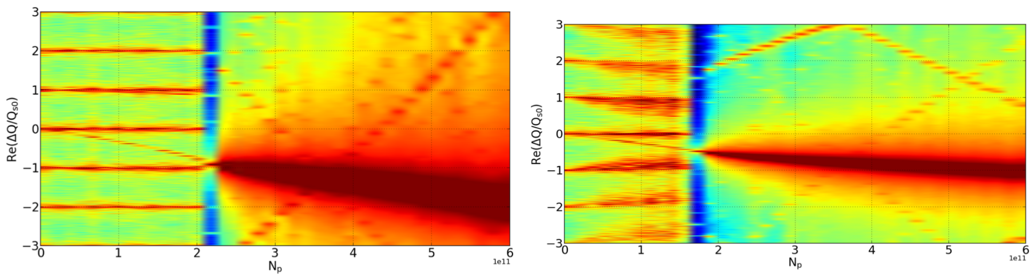

Figure 2: Real part of the frequency shift of the low-order coherent oscillation modes as a function of the bunch population without beamstrahlung, considering only the transverse impedance (left) or both the transverse and longitudinal impedance (right).

threshold reduction is due to a spread of the synchrotron frequencies introduced by the longitudinal wakefield.

5. Possible mitigation strategies

One method that can be used to mitigate the TMCI instability exploits the chromaticity. Nonzero lattice chromaticity induces a spread in the betatron tunes, which could stabilise the beam. Simulations indicate a slight improvement with a positive chromaticity, but the threshold remains below the nominal beam intensity.

The long-range transverse wakefield due to the RW also produces a coupled bunch instability with a rise time that depends on the fractional part of the tune. For the parameter list of Table 1, the rise time of this instability is about 2 ms, corresponding to 6 revolutions, and it can be cured with a robust bunch-by-bunch feedback system. The same feedback system also affects the TMCI. Indeed, by acting on the centre of mass of each bunch, the feedback counteracts the shift of the 0 mode toward the -1 one. On the other hand, the same feedback could induce an instability of the

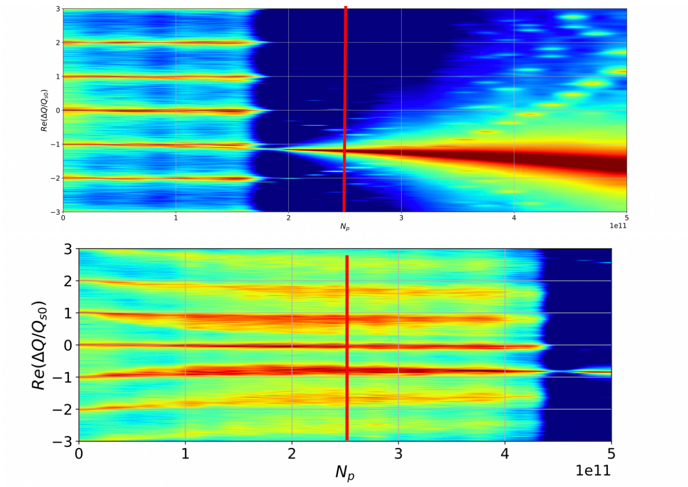

Figure 3: Mode analysis considering, on the top, only the transverse wakefield with resistive feedback having a damping time of 10 turns, on the bottom, transverse and longitudinal wakefield with resistive feedback having a damping time of 4 turns.

−1 mode [15], with a threshold depending on the complex phase of the feedback itself. For a pure reactive feedback, with only the effect of the transverse wakefield, the instability threshold is even lower than that of TMCI, as shown on the top of Fig. 3.

However, this instability of the −1 mode, or ITSR [15], has a growth rate not as dramatic as that of the TMCI, and it can rather easily be cured by means of Landau damping. Indeed, the synchrotron tune spread due to the longitudinal wakefield suffices to increase the instability threshold from $18{\times}10^{10}$ to $46{\times}10^{10}$ particles per bunch, as is illustrated in the bottom part of Fig. 3.

Finally, we note that these results were obtained for a single beam without beamstrahlung. For a self-consistent evaluation, simulations which also include the beam-beam effects are necessary. In general, the increased energy spread due to beamstrahlung helps to stabilize the beam.

6. Conclusion

Considering an updated model of the FCC-ee machine impedance, we simulated single bunch collective effects in the transverse and longitudinal planes for the main ring of the Z pole machine. At nominal intensity, the longitudinal beam dynamics is stable only in collisions, thanks to the beamstrahlung effect. Otherwise, because of the longitudinal wakefields, we are in the microwave instability regime, which manifests itself through an anomalous increase of bunch length and energy spread. The longitudinal wakefield also has a profound impact on the transverse dynamics. In fact, its inclusion in the simulations decreases the TMCI threshold. However, this instability is kept under control by a strong resistive transverse feedback, used to mitigate the transverse coupled bunch instability. In this case the longitudinal wakefields seem to play a beneficial role suppressing the eventual ITSR instability, as discussed in Sec. 5.

In future work, the FCC-ee machine impedance model will need to be further extended to include other important impedance sources, as those due to the collimation system, while examining any consequent changes in instability thresholds and beam dynamics.

Acknowledgements

This work was supported by the European Union's Horizon 2020 Research and Innovation programme under grant no. 951754 (FCCIS).

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