COUPLING IMPEDANCES AND COLLECTIVE EFFECTS FOR FCC-ee

E. Belli*, M. Migliorati, University of Rome La Sapienza, Rome
G. Castorina, B. Spataro, M. Zobov, INFN/LNF, Frascati (Rome)
A. Novokhatski, SLAC, Menlo Park, California
S. Persichelli, LBNL, Berkeley, California

Abstract

A very important issue for the Future Circular Collider (FCC) is represented by collective effects due to the self-induced electromagnetic fields, which, acting back on the beam, could produce dangerous instabilities. In this paper we will focus our work on the FCC electron-positron machine: in particular we will study some important sources of wake fields, their coupling impedances and the impact on the beam dynamics. We will also discuss longitudinal and transverse instability thresholds, both for single bunch and multibunch, and indicate some ways to mitigate such instabilities.

INTRODUCTION

The FCC-ee is an e^+e^- circular collider designed to cover the beam energy range from the Z pole (45.6 GeV) to the top pair threshold (175 GeV). It would be the first step towards the FCC-hh [1], a 100 TeV hadron collider in the same tunnel of 97.75 km. Collective effects represent a serious issue for such a kind of machine, since they can produce instabilities and limit its operation and performance. In this paper we will focus on single bunch and multi bunch instabilities for the Z pole caused by the resistive wall (RW) and describe other important impedance sources, i.e. Beam Positions Monitors (BPMs), tapers and bellows with RF fingers. For reference, Table 1 shows the FCC-ee beam parameter list used for these studies [2].

Table 1: FCC-ee Beam Parameter List

Beam energy [GeV]	**45.6**
Circumference C [km]	97.75
Bunches/beam	73770
Bunch population [10^{11}]	0.4
Beam current I [A]	1.45
Rf frequency f_{RF} [MHz]	400
RF voltage V_{RF} [MV]	88.8
Momentum compaction $\alpha_c[10^{-5}]$	1.465
Bunch length σ_z [mm]	3.6
Energy spread σ_e [%]	0.037
Betatron tunes $Q_x \backslash Q_y$	265.14\267.22
Synchrotron tune Q_s	0.0234

RESISTIVE WALL WAKE FIELDS

When the beam passes through the vacuum chamber, it induces currents on the pipe walls. If the beam pipe walls have a finite resistivity, these currents extend behind the position of the charges, creating electromagnetic fields which can act on the following particles and perturb their motion by increasing the amplitude of their oscillations. This instability can occur in both longitudinal and transverse directions [3,4]. In the following, we will focus on the main single bunch effects due to the RW on the beam dynamics, by considering a 35 mm radius vacuum chamber with three layers (a first layer of copper with 2 mm thickness [5], then 6 mm of dielectric and finally iron with resistivity $\rho = 10^{-7}\Omega m$) and different coatings of the pipe walls:

- Amorphous Carbon (AC)
  thk = 200 nm, $\rho = 10^{-4}$ Ωm [5]
- Non-Evaporable Getter (NEG)
  thk = 1μm , $\rho = 10^{-6}$ Ωm [6]
- Titanium Nitride (TiN)
  thk = 200 nm, $\rho = 0.5 \cdot 10^{-6}$ Ωm [7, 8]

All these materials are characterized by a low Secondary Electron Yield (SEY) and a low desorption yield that could reduce significantly the electron cloud build up in the machine [9, 10]. Figure 1 shows the real and imaginary part of the transverse and longitudinal impedances due to RW as a function of the frequency for all the cases mentioned above. These impedances have been obtained from the Impedance-Wake2D code [11] and will be used in the following to analyze the effects of the RW on the beam dynamics.

Single Bunch Effects

This section is focused on the most important effects of the RW on the single bunch dynamics: the Microwave Instability (MI) and the Transverse Mode Coupling Instability (TMCI) in the longitudinal and transverse planes, respectively. These two kinds of instability can limit the bunch intensity in the accelerator: it is well known from the theory [12] that the frequencies of the intra-bunch modes depend on the bunch intensity and as it increases the mode frequencies shift and merge, giving rise to the instability. The instability threshold is localized in the point where there is the mode coupling. Above this threshold, the bunch is lost in the transverse case while in the longitudinal case there is an increase of the bunch length and the energy spread and sometimes bunch internal oscillations can be observed which could be particular harmful in beam-beam collisions.

MI In order to evaluate the MI threshold, several simulations were performed by using the macroparticle tracking codes PyHEADTAIL [13] and SBSC [14, 15]. Figs. 2, 3

* eleonora.belli@roma1.infn.it

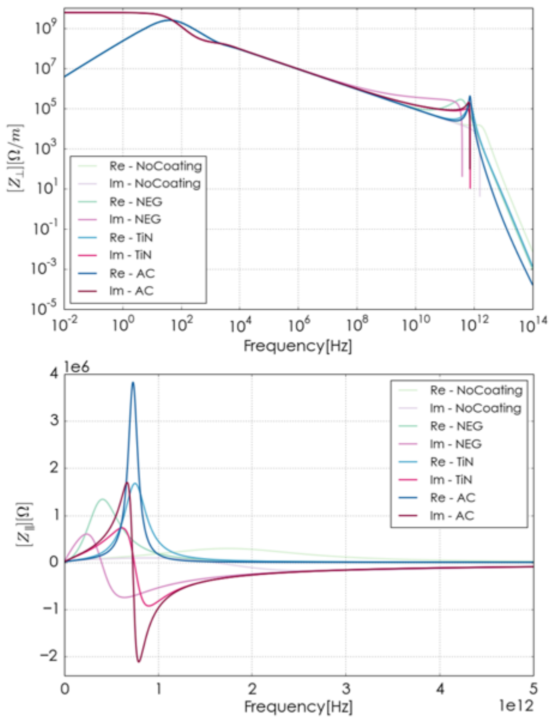


Figure 1: Real and imaginary part of the transverse (top) and longitudinal (bottom) RW impedances as a function of the frequency in the case of no coating, NEG coating, TiN coating and Carbon coating.

show the bunch lengthening and the energy spread increase due to the RW wakes for all the coatings under study. The NEG coating gives a MI threshold around the nominal bunch population, while the threshold for TiN and AC coatings is about $1.6 - 1.8 \cdot 10^{11}$, i.e. four times larger than the nominal intensity.

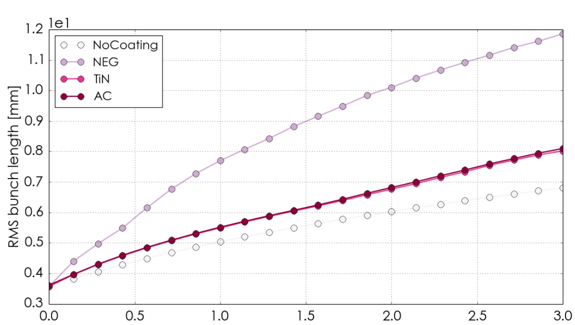


Figure 2: RMS bunch length as a function of the bunch intensity given by PyHEADTAIL by considering only the RW impedance in the case of no coating and NEG, TiN and AC coatings.

TMCI As in the longitudinal case, the TMCI threshold has been evaluated with PyHEADTAIL, by including also the bunch lengthening due to the longitudinal wake of Fig. 2. All the coatings show a good margin of safety. As an example, Fig. 4 shows the real part of the frequency shift of the first two radial modes for the first five azimuthal modes going from -2 to 2 as a function of the bunch population, in the case of Carbon coating.

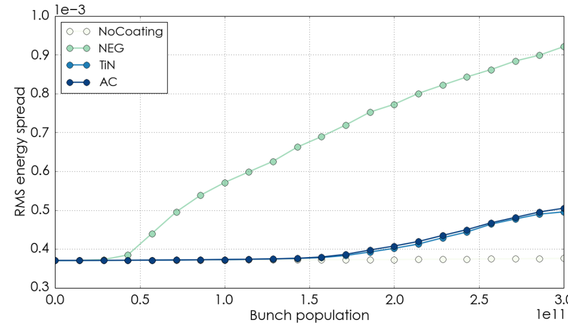


Figure 3: RMS energy spread as a function of the bunch intensity given by PyHEADTAIL by considering only the RW impedance in the case of no coating and NEG, TiN and AC coatings.

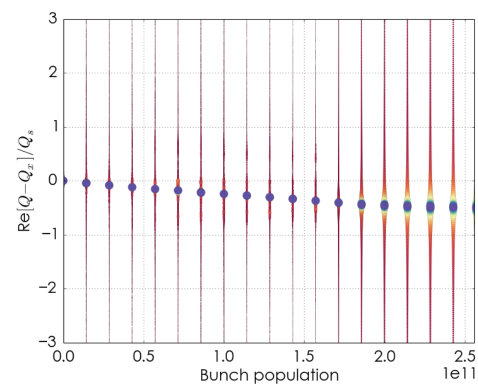


Figure 4: TMCI threshold evaluated with PyHEADTAIL by taking into account the bunch lengthening due to the longitudinal wake in the case of Carbon coating.

Multi Bunch Effects

In case of long range transverse and longitudinal wake fields, coupled bunch modes have to be taken into account. In the transverse plane, the instability growth rate depends on the real part of the coupling impedance [3,4] which depends in turn on the sign of the frequency. This means that modes will be unstable for negative frequencies. With the parameter list given in Table 1, the most dangerous coupled bunch mode is $\mu = 73504$ with the lowest negative frequency shown in Fig. 5. The corresponding growth rate is about 494.8 s^{-1}, which means a rise time of about 6 turns. Therefore, a robust feedback is necessary to cope with the fast instability. For the longitudinal case, refer to [3, 4].

OTHER IMPEDANCE SOURCES

Besides the RW, there are other important sources of impedance in the machine to be studied with particular care.

ISBN 978-3-95450-182-3

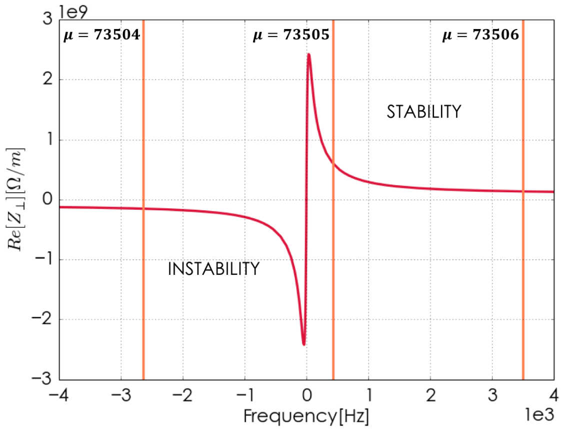


Figure 5: Coupled bunch spectrum and real part of the RW impedance in the case of no coating as a function of the frequency for the fractional tune $\nu_\beta = 0.14$.

In [3, 4, 9], the beam coupling impedance for the interaction region vacuum chamber, synchrotron light absorbers and RF cavities with tapers has been evaluated. In addition to these impedance sources, diagnostic elements like four-button BPMs [16] (Fig. 6.a) are planned to be installed in the machine, for a total number of about 4000. Because of the particular shape of the vacuum chamber in the arcs [17], a special type of winglet-to-circular tapers (Fig. 6.b) has been designed for this purpose, for a total number of 4000 double tapers. 8000 bellows with RF fingers (Fig. 6.c) will be installed before and after each BPM. In order to evaluate the contribution of these other devices to the machine impedance budget, CST [18] wakefield simulations in time domain were performed by using a Gaussian bunch of 4mm RMS bunch length. As example, the longitudinal wake potentials are shown in Fig. 7 and compared with the RW one, computed analytically as the convolution between the wakefield obtained from ImpedanceWake2D in the case of no coating and a 4mm Gaussian bunch. It is clear that the contributions of tapers and bellows cannot be neglected and their impact on the beam dynamics would result in a decrease of the MI threshold. In principle, it would be possible to avoid tapers and use different designs for flanges and bellows, for example the comb-type RF shield proposed for KEK [19].

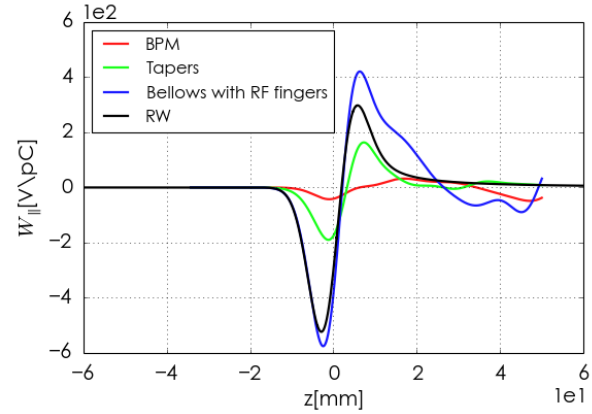
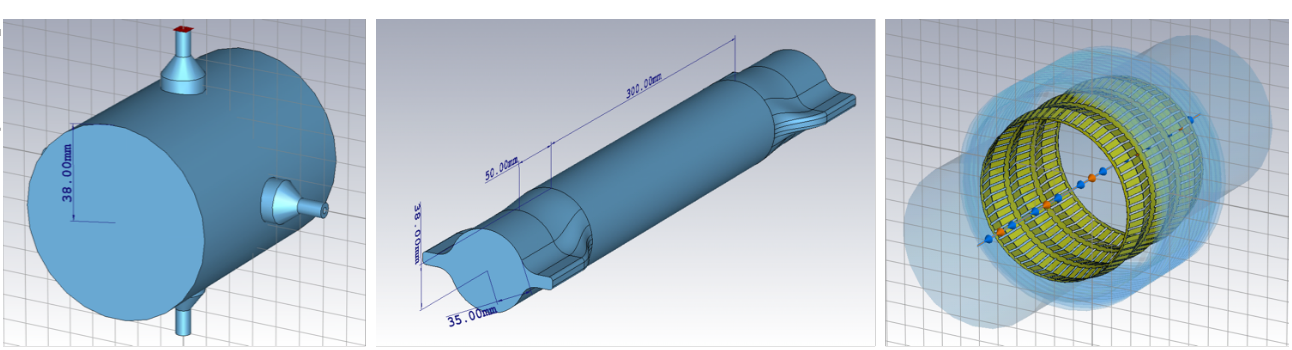


Figure 7: Longitudinal wake potentials for a 4mm Gaussian bunch given by RW, BPMs, tapers and bellows with RF fingers.

CONCLUSIONS

In this paper we have presented the most important collective effects issues for FCC-ee. In particular, the MI threshold is around the nominal bunch intensity for the NEG coating while it is about a factor of 4 higher in the case of TiN and AC. The single bunch TMCI does not seem to be dangerous: its threshold is far beyond the nominal bunch intensity. The rise time of the transverse multibunch instability is as fast as 6 revolution turns: this means that a robust feedback system is required for the instability suppression. The geometric impedance has been evaluated for many vacuum chamber components showing that these elements can give contributions comparable with the RW one. Our studies have indicated that the considered Sirius BPM design is a good candidate from the impedance point of view while the impedance due to the other devices can be improved by reducing the number of tapers (by placing BPMs and quadrupoles on the vacuum chamber with winglets) and considering the use of the comb-type bellows and flanges similar to those of SuperKEKB.



a) b) c)

Figure 6: CST models of BPMs, tapers and bellows with RF fingers.

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ISBN 978-3-95450-182-3