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SINGLE BUNCH INSTABILITIES IN FCC-ee

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Abstract

FCC-ee is a high luminosity lepton collider with a centre-of-mass energy from 91 to 365 GeV. Due to the machine parameters and pipe dimensions, collective effects due to electromagnetic fields produced by the interaction of the beam with the vacuum chamber can be one of the main limitations to the machine performance. In this frame, an impedance model is required to analyze these instabilities and to find possible solutions for their mitigation. This paper will present the contributions of specific machine components to the total impedance budget and their effects on the beam stability. Single bunch instability thresholds will be estimated in both transverse and longitudinal planes.

INTRODUCTION

Within the Future Circular Collider studies at CERN [1] which aim to design post-LHC particle accelerators, the high luminosity e^+e^- circular collider FCC-ee is considered as a possible first step towards FCC-hh, a 100 TeV hadron collider in the same tunnel of 97.75 km. The lepton collider has been designed to cover the beam energy range from 45.6 GeV to 182.5 GeV to study the properties of the Z resonance, the W and top pair thresholds and the Higgs boson with unprecedent precision. Table 1 summarizes the main beam parameters at Z running, which represents the most challenging scenario from the instability point of view. This paper focuses on the impedance model and collective beam instabilities induced by wakefields in the lowest energy case. It describes the effects of the main machine components on the single bunch beam dynamics in both transverse and longitudinal planes, giving special attention to the resistive wall (RW) impedance which represents the main source of wakefields in the machine.

RESISTIVE WALL IMPEDANCE

This section focuses on the impact of the RW impedance on the single bunch dynamics. For these studies, the vacuum chamber is assumed to be circular with 35mm radius and three layers: a first inner layer of copper with 2mm thickness, then 6mm of dielectric and finally iron with resistivity $\rho = 10^{-7}\Omega$-m. A coating of the copper surface is foreseen to reduce the Secondary Electron Yield (SEY) of the surface (for the mitigation of the electron cloud build up in the machine) and to improve the pumping system for an optimum vacuum environment during operation. On the basis of the positive experience of the LHC warm sections [2], it was decided to use Ti-Zr-V Non Evaporable Getter (NEG) films in order to ensure the required pressure and low background.

Table 1: FCC-ee baseline beam parameters, where SR and BS stand for synchrotron radiation and beamstrahlung.

Beam energy [GeV]	**45.6**
Circumference C [km]	97.75
Number of bunches/beam	16640
Bunch population N_p [10^{11}]	1.7
Beam current I [A]	1.39
RF frequency f_{RF} [MHz]	400
RF voltage V_{RF} [MV]	100
Energy loss per turn [GeV]	0.036
Momentum compaction $\alpha_c[10^{-5}]$	1.48
Bunch length $\sigma_{z,SR}/\sigma_{z,BS}$ [mm]	3.5/12.1
Energy spread $\sigma_{dp,SR}/\sigma_{dp,BS}$ [%]	0.038/0.132
Horizontal tune Q_x	269.138
Vertical tune Q_y	269.22
Synchrotron tune Q_s	0.025
Horizontal emittance ϵ_x [nm]	0.27
Vertical emittance ϵ_y [pm]	1.0

Previous studies [3] pointed out that in the case of FCC-ee the typical NEG film thickness of 1μm makes the RW impedance responsible of quite low single bunch instability thresholds, in both transverse and longitudinal planes. It has been demonstrated [4] that under certain assumptions the longitudinal and transverse impedances of a two-layer beam pipe are given by the sum of two terms, one representing the impedance of a single layer pipe and a second term representing an inductive perturbation proportional to the thickness Δ of the coating:

$$\frac{Z_{\parallel}(\omega)}{C} \simeq \frac{Z_0\omega}{4\pi cb}\left\{[\mathrm{sgn}(\omega) - i]\,\delta_2 - 2i\Delta\left(1 - \frac{\sigma_1}{\sigma_2}\right)\right\}$$

$$\frac{Z_{\perp}(\omega)}{C} \simeq \frac{Z_0}{2\pi b^3}\left\{[1 - i\mathrm{sgn}(\omega)]\,\delta_2 - 2i\Delta\mathrm{sgn}(\omega)\left(1 - \frac{\sigma_1}{\sigma_2}\right)\right\}$$

where Z_0 is the vacuum impedance, c the speed of light, b the pipe radius and δ_1,σ_1 and δ_2,σ_2 the skin depths and conductivities of the coating and the substrate, respectively. If $\frac{\sigma_1}{\sigma_2} << 1$ (condition always verified in the FCC-ee case, also taking into account the variation of the NEG resitivity with frequency [5]), then the second term becomes independent on the conductivities of the materials and the effects of the impedances on the single bunch dynamics are affected mainly by the thickness of the coating.

NEG Thin Films: Experimental Results

In this context, NEG thin films with thicknesses below 250 nm have been investigated to find the minimum effective thickness ensuring at the same time a good activation performance for vacuum pumping, a low SEY to minimize the

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electron cloud build up in the machine and a reduction of the RW impedance contribution to ensure beam stability during operation. Copper samples have been coated with NEG thin films at thicknesses of 1000nm, 200nm, 100nm and 50nm via DC magnetron sputtering [6], obtaining actual thicknesses of 1100nm, 203nm, 87nm and 30nm, respectively. The surface composition was measured by X-ray Photoelectron Spectroscopy (XPS) and the activation performance was evaluated by the reduction of the area of the oxygen peak O1s during a cycle of 4 hours up to a temperature of $250^\circ C$. Figure 1 shows the O1s peak area as a function of the activation temperature: from the activation performance point of view, a good candidate for coating is the 100nm thickness that also ensures a margin of safety for the stability, as we will see in the next section. This experimental activity also includes SEY measurements presented in [7].

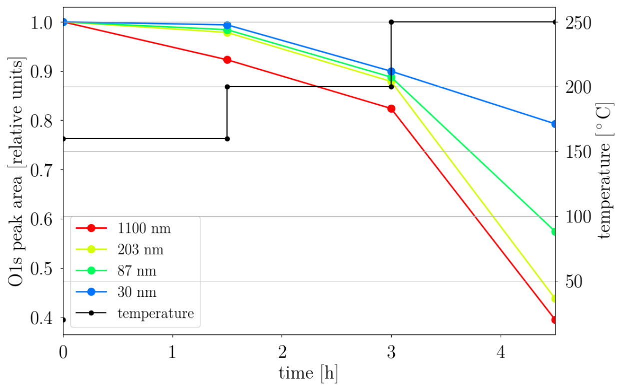

Figure 1: Activation performance: reduction of the area of the oxygen peak from the XPS spectrum after the fourth activation cycle.

The Impact of Thickness on Beam Dynamics

The most important effects of the RW impedance on the single bunch dynamics are the Microwave Instability (MI) in the longitudinal plane and the Transverse Mode Coupling Instability (TMCI) in the transverse plane. Numerical simulations with the macroparticle tracking code PyHEADTAIL [8] were performed to study the impact of the coating thickness on the instability thresholds. For these studies, NEG thin films with thicknesses of 1100nm, 200nm, 100nm and 50nm have been considered. The beam parameters used for simulations are listed in Table 1.

MI Figures 2 and 3 show the bunch lengthening and the energy spread increase due to the longitudinal RW wakefield as a function of the bunch population for all the thicknesses under study. As mentioned before, a coating of 1µm thickness makes the bunch unstable, while the thinner film of 100nm allows to increase the MI threshold by a factor 7.

TMCI The TMCI threshold has been evaluated with the analytical Vlasov solver DELPHI [9] by taking into account the bunch lengthening due to the longitudinal wake (Fig 2).

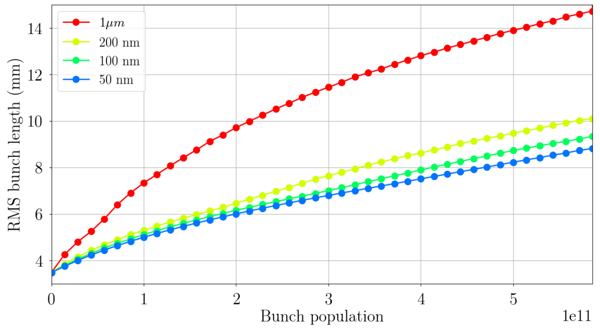

Figure 2: RMS bunch length as a function of the bunch population given by numerical simulations by considering only the RW impedance produced by NEG films with different thicknesses.

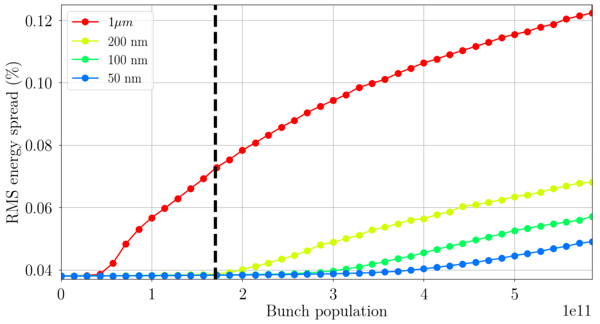

Figure 3: RMS energy spread as a function of the bunch population given by numerical simulations by considering only the RW impedance produced by NEG films with different thicknesses. The black dashed line represents the nominal bunch population.

In the transverse case, the instability threshold is affected to a lesser extent by the coating thickness, because it is increased by the higher bunch length at the same intensity. As shown in Fig. 4, for a coating of 100nm thickness the TMCI threshold is about a factor 2.5 higher than the nominal bunch intensity.

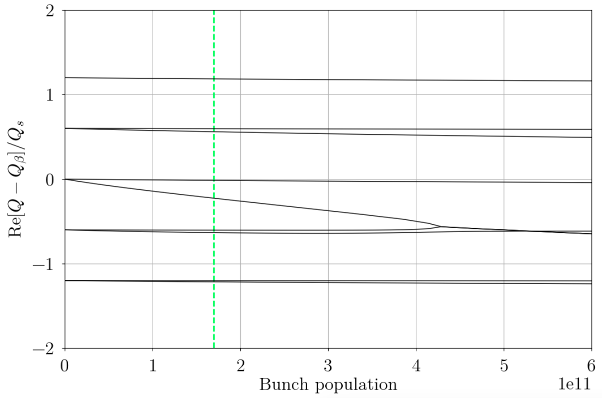

Figure 4: Real part of the frequency shift of the first coherent oscillation modes as a function of the bunch population for 100nm coating. The green dashed line represents the nominal bunch intensity.

OTHER IMPEDANCE SOURCES

In addition to the RW impedance, there are other sources of wakefields in the machine. At Z running, the RF system consists of 52 cavities at 400 MHz with a single cell [10] that will be arranged in groups of four cavities connected by 26 0.5m long tapers. In order to cut off the beam halo and to suppress the background, collimators based on PEP-II and SuperKEKB design [11, 12] are planned to be installed in the machine, for a total number of 20 (10 for each plane). The impedance contribution of the 10000 absorbers to cope with the synchrotron radiation (SR) has been minimized by using a circular chamber with 35mm radius and two rectangular antechambers on both sides, where the SR absorbers will be installed. This model also includes 4000 Beam Position Monitors [13] and 8000 comb-type bellows with RF shielding [14] to be installed before and after each BPM.

Longitudinal Impedance Model

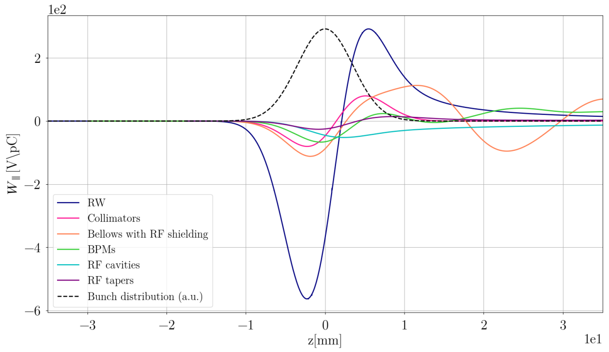

Figure 5: Longitudinal wake potentials for a Gaussian bunch with nominal bunch length $\sigma_z = 3.5$ mm due to the main FCC-ee components compared with the RW contribution (blue line).

The contribution of all the current machine components to the longitudinal impedance budget has been evaluated by means of ABCI [15] and CST [16] simulations in time domain for a Gaussian bunch with nominal bunch length of $\sigma_z = 3.5mm$. Figure 5 shows the longitudinal wake potentials of each component. Table 2 summarizes the corresponding loss factors. The major contribution to the machine impedance is given by the RW with a total loss factor at nominal intensity and bunch length of 210 V/pC. The total dissipated power at nominal intensity is 13.6 MW, about a factor 3.7 smaller than the total SR power dissipated by the beam of 50 MW. However, this value of power loss is expected to be lower due to the bunch lenghtening effect. By using as Green function for the PyHEADTAIL code the wake potential of a bunch with $\sigma_z \simeq \frac{1}{10}\sigma_{z,nom}$, the MI threshold has been evaluated by considering all the current machine components and 100nm NEG coating and is about $2.5 \cdot 10^{11}$, a factor of 1.5 larger than the nominal bunch intensity, as shown in Fig. 6.

Table 2: Power loss contribution of the main FCC-ee components at nominal intensity and bunch length, in the lowest energy case of 45.6 GeV.

Component	**Number**	k_{loss}[V/pC]	P_{loss}[MW]
Resistive wall	97.75km	210	7.95
Collimators	20	18.69	0.7
RF cavities	52	17.14	0.65
RF double tapers	13	24.71	0.93
BPMs	4000	40.11	1.5
Bellows	8000	49.01	1.85
Total		**359.6**	**13.6**

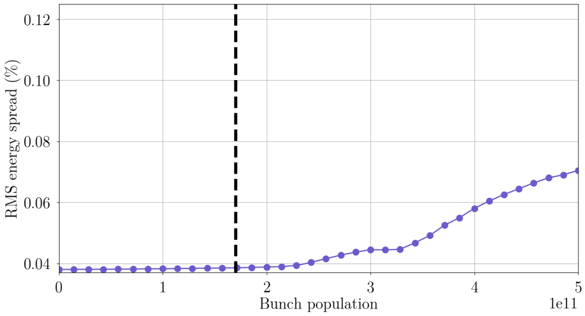

Figure 6: RMS energy spread as a function of the bunch population given by numerical simulations by considering the impedance contribution of all the machine components. The black dashed line represents the nominal bunch intensity.

CONCLUSIONS

In this paper we have presented the main sources of impedance in FCC-ee and their effects on the single bunch dynamics. The RW impedance represents the main source of wakefields in the machine and its contribution to the impedance budget can be reduced by decreasing the thickness of the coating needed for pumping and electron cloud mitigation. Numerical simulations and experimental results have indicated that the 100nm thickness is a good candidate for coating, satisfying at the same time impedance, vacuum and electron cloud requirements. The geometric impedance has been evaluated for important machine components showing that the contribution of these elements is up to 5 times smaller than the RW one. The MI instability threshold is around $2.5 \cdot 10^{11}$, about a factor of 1.5 higher than the nominal bunch intensity. However, it is important to mention that operation with beamstrahlung allows to further increase the instability thresholds in both planes, due to the higher bunch length and energy spread.

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REFERENCES

[1] Future Circular Collider Study, `https://fcc.web.cern.ch`

[2] P.C. Pinto, "History and potential of Non Evaporable Getter (NEG) technology", presented at Workshop on Advanced Materials and Surfaces, 19-20 November 2013, CERN, Geneva, Switzerland, `https://indico.cern.ch/event/229108/contributions/1539894/`

[3] E. Belli, "Impedance model and collective effects for FCC-ee", presented at FCC Week 2017, Berlin, Germany, `https://indico.cern.ch/event/556692/contributions/2590409/`

[4] M. Migliorati, E. Belli and M. Zobov, "Impact of the resistive wall impedance on beam dynamics in the Future Circular e+e- Collider", *Phys. Rev. Accel. Beams*, vol. 21, p. 041001, 2018.

[5] E. Koukovini Platia, "High Frequency Effects of Impedances and Coatings in the CLIC Damping Rings", CERN, Geneva, Switzerland, Rep. CERN-THESIS-2015-152.

[6] P. Chiggiato, P. Costa Pinto, "Ti-Zr-V nonevaporable getter films: From development to large scale production for the Large Hadron Collider", *Thin Solid Films*, vol. 515, 2006.

[7] E. Belli *et al.*, "Electron cloud studies in FCC-ee", paper MOPMK012, this conference.

[8] PyHEADTAIL, `https://github.com/PyCOMPLETE/PyHEADTAIL`

[9] DELPHI, `https://twiki.cern.ch/twiki/bin/view/ABPComputing/DELPHI`

[10] A. Butterworth, "Cavity design and beam-cavity interaction", presented at FCC Week 2017, Berlin, Germany, `https://indico.cern.ch/event/556692/contributions/2484361/`

[11] S. DeBarger *et al.*, "The PEP-II movable collimators", No. SLAC-PUB-11752, 2001.

[12] T. Ishibashi *et al.*, “Low impedance movable collimators for SuperKEKB”, in *Proc. IPAC'17*, Copenhagen, Denmark, May 14-19, 2017.

[13] H.O.C. Duarte, L. Sanfelici, and S.R. Marques, "Design and impedance optimization of the SIRIUS BPM button", in *Proc. IBIC2013,* Oxford, UK, Sep. 16-19, 2013.

[14] Y. Suetsugu, M. Shirai, and K. Shibata, "Possibility of comb-type rf shield structure for high-current accelerators", *Phys. Rev. ST Accel. Beams*, vol. 6, p. 103201, 2003.

[15] ABCI, `http://abci.kek.jp/abci.htm`

[16] CST, `https://www.cst.com`