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STUDIES AND MITIGATION OF TMCI IN FCC-ee*

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Abstract

Previous studies have identified turbulent mode coupling instability (TMCI) as one of the most severe single-bunch instabilities in the FCC-ee collider, potentially limiting its performance. Its threshold is influenced by both transverse and longitudinal wakefields arising from vacuum chamber resistive wall effects, discontinuities, and beam-beam interactions, the latter of which can be seen as a transverse cross-wake force.

In this paper, we investigate the TMCI using the most recent collider parameters and an updated impedance model. We also explore various mitigation techniques aimed at increasing the instability threshold, including positive chromaticity and a feedback system.

INTRODUCTION

As the Future Circular Collider (FCC) project progresses, encompassing both hadron [1] (FCC-hh) and electron-positron [2] (FCC-ee) colliders within a single tunnel at CERN, ongoing developments influence its design. The FCC-ee collider is envisaged to operate across four energy stages: 45.6, 80, 120, and 182.5 GeV, for research activities on the characteristics of fundamental particles such as the Higgs, W, and Z bosons, as well as the threshold for top quark pair production.

With the continuous refinement of the machine's design, the coupling impedance budget evolves alongside updates to vacuum chamber components. Consequently, the understanding of collective effects and instability thresholds necessitates ongoing reassessment.

In this paper, we focus our study on the TMCI of the lowest energy operation, which is the most challenging from the collective effects point of view. In particular, we have observed that the longitudinal and transverse wakefields, the chromaticity and the feedback systems influence the instability threshold. Besides, we have evaluated the effect of beam-beam interaction since in the colliders exploiting the crab waist collision scheme with a large Piwinski angle [3] the threshold of the vertical instability can be substantially affected by beam-beam [4]. Other previous works on this subject can be found in refs. [5–13].

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UPDATED PARAMETER LIST

The main parameters used for the study of the collective effects are listed in Table 1. In particular, compared to the previous parameter list used in [13], we have now a reduced single bunch population and a longer zero current bunch length. Also, some beam-beam parameters have changed.

Table 1: Main Parameters used for Collective Effects Beam Dynamics Studies

Parameter	**Value**
Circumference (km)	90.658816
Beam energy (GeV)	45.6
Bunch population (10^{11})	2.14
RF frequency (MHz)	400
RF Voltage (MV)	79
Energy loss per turn (GeV)	0.0391
Longitudinal damping time (turns)	1158
Momentum compaction factor 10^{-6}	28.6
Horizontal tune/IP	54.5395
Vertical tune/IP	55.55
Synchrotron tune	0.0288
Emittance Hor (nm)/Vert (pm)	0.71/1.9
Bunch length (mm) (SR/BS)*	5.6/15.4
Energy spread (%) (SR/BS)*	0.039/0.109
Piwinski angle (BS)*	26.4
ξ_x/ξ_y	0.0022/0.097
β^* Hor (m)/Vert (mm)	0.11/0.7
Luminosity/IP (10^{34}/cm^{2}s)	141

*SR: synchrotron radiation, BS: beamstrahlung

IMPEDANCE MODEL

In parallel with the parameter list, some machine devices have been modified, too. The resistive wall (RW) due to the vacuum chamber has always represented the most important impedance source. The circular beam pipe, made of copper coated with a 150 nm thin layer of a non-evaporable getter (NEG) used for pumping purposes and electron cloud suppression, has two additional lateral winglets for synchrotron radiation absorbers [10] and symmetry reasons. Since their contribution to the impedance is negligible compared to the circular pipe, here we only consider the RW contribution of a circular geometry.

Due to the too-high power consumption requested for driving quadrupole and sextupole magnets, the new FCC-ee baseline foresees a beam pipe radius b reduced from 35

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to 30 mm. As a rule of thumb, since the transverse RW impedance is proportional to b^{-3}, we expect an increase of this contribution of about 60%. Indeed, in Fig. 1 we compare the previous and the updated model as given by IW2D code [14]. For example, around 30 GHz, both the real and imaginary parts of the impedance increase by a factor of about 1.5. In addition to this increased contribution, we must also consider that the other devices evaluated so far (except the already updated collimators) will increase their impedance, even if not with the same scaling factor.

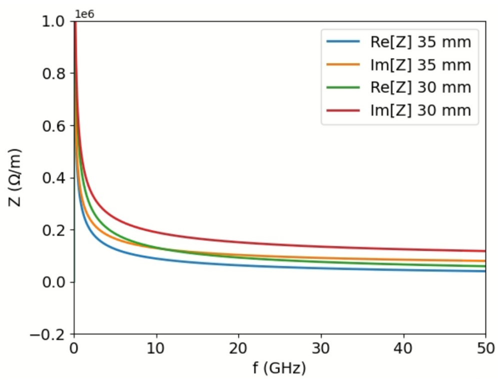

Figure 1: Transverse dipolar resistive wall impedance with 35 and 30 mm pipe radius.

The collimation system represents another important impedance source. Only its RW contribution is currently included by considering parallel plates since the geometrical part is still under study [15]. In FCC-ee we have two types of collimators: the beam halo collimators, which limit the detector backgrounds and protect sensible machine equipment [16], and the synchrotron radiation collimators used to intercept photons upstream of the interaction points. For the first ones, since the machine optics have been updated, their geometric dimensions and the beta function at their locations are also changed compared to the previous study presented in [13]. In particular, as shown in Table 2 [17], the primary collimators (named 'tcp...') have a reduced length that has passed from 0.4 to 0.25 m. Recently, an analogous table has been defined for the synchrotron radiation collimators [17], too. Their local beta function is higher than that of the beam halo collimators. However, their length is smaller (10 cm), the half gap is generally larger, and they are made of tungsten, having a conductivity much higher than that of MoGr. For all these reasons their RW impedance is much smaller than that of the primary beam halo collimators.

From the table, we can also deduce that the vertical primary collimator tcp.v.b1 gives the highest resistive wall transverse dipolar impedance contribution in both the horizontal and vertical planes, having the smallest gap and a very high local beta function.

In addition to the above-discussed devices, we have considered 10000 bellows, 7000 BPMs, 56 single-cell 400 MHz cavities grouped in 14 cryomodules, each one with a double taper. Except for the RF cavities, the design of the other devices is still under development. However, we have evaluated their impedance by using a geometry taken from other accelerators in order to have an initial estimation of their contribution to the total impedance model.

Table 2: Halo Collimators

Name	l **(m)**	$g/2$ **(mm)**	β_x **(m)**	β_y **(m)**
tcp.h.b1	0.25	6.7	517.46	724.70
tcp.v.b1	0.25	2.4	518.59	725.79
tcs.h1.b1	0.3	3.7	116.99	766.52
tcs.v1.b1	0.3	2.5	422.97	578.88
tcs.h2.b1	0.3	5.1	215.59	215.59
tcs.v2.b1	0.3	2.9	32.91	803.95
tcp.hp.b1	0.25	4.2	71.67	125.83
tcs.hp1.b1	0.3	4.6	63.91	193.84
tcs.hp2.b1	0.3	16.7	853.47	384.47

In the collimators' Name, 'p' stands for primary (made of MoGr), 's' for secondary (made of Mo), 'v' for vertical, and 'h' for horizontal. Additionally, $l \rightarrow$ length, $g \rightarrow$ full gap.

In Fig. 2 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.

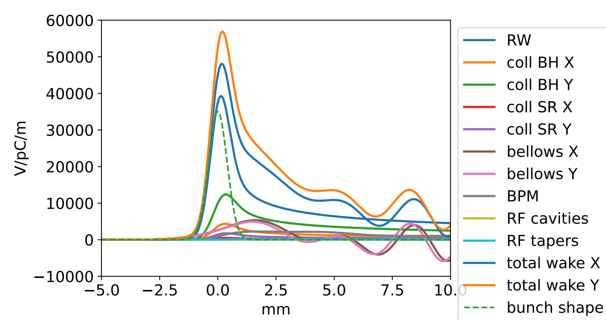

Figure 2: Transverse dipolar wake potential of 0.4 mm Gaussian bunch.

TURBULENT MODE COUPLING INSTABILITY

An important effect of the transverse wakefield is the excitation of the TMCI [18], which occurs when the frequencies of some coherent transverse oscillation modes of a bunch shift and couple together. In particular, for FCC-ee, we observe a shift of the '0' mode towards the '-1' one, up to their merging with consequent instability.

Previous beam dynamics simulations were performed with PyHEADTAIL code [19] that was initially compared with other tracking codes [20, 21], giving a very good agreement. For this study, we used XSuite, a collection of Python packages for the simulation of the beam dynamics in particle accelerators with the possibility of including several effects [22]. Preliminary comparisons were performed with PyHEADTAIL giving the same results. The coherent frequencies of the lowest order oscillation modes of a bunch can be obtained from the results of XSuite with a proper analysis described in [23].

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In Fig. 3 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 in the presence of both longitudinal and transverse wakefields. As it can be seen, the TMCI threshold, observed when the zero mode coherent frequency shifts and couples with the -1 mode, occurs at a bunch population $N_p \simeq 10^{11}$, much lower than the nominal bunch population. The influence of the longitudinal wakefield can be observed by performing simulations under the unphysical condition of the only presence of the transverse wakefield. In this case, we observe a slightly higher instability threshold, at about 1.2×10^{11}. The reason is that the longitudinal wakefield introduces a spread of the transverse coherent oscillation frequencies and reduces the tune separation between the coherent frequencies of the zero and the '-1' oscillation mode.

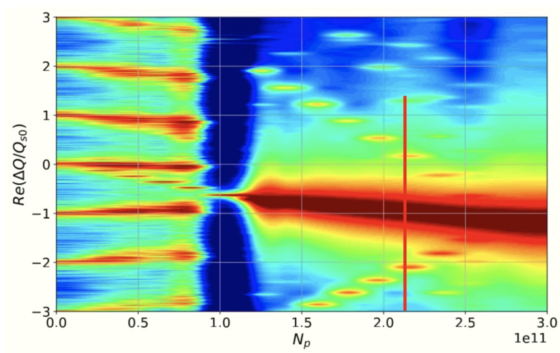

Figure 3: Real part of the normalized tune shift of the first azimuthal transverse coherent oscillation modes vs bunch population.

MITIGATIONS

One action that can be taken to mitigate the TMCI is working with a slightly positive chromaticity Q'. Still, simulations show that the TMCI threshold increases very little and remains well below the nominal bunch population.

In addition to the TMCI, the real part of the transverse resistive wall impedance at low frequency can excite the coupled bunch instability, which, depending on the fractional part of the betatron tune, can be mitigated by a proper feedback system. It is worth reminding that, with such feedback, another type of instability of the single mode '-1' [24] could arise. Such instability has also been observed and suppressed at SuperKEKB [25] by properly tuning the feedback system. Such bunch-by-bunch feedback, in combination with the longitudinal wakefield and a positive chromaticity, also mitigates the TMCI [26]. Indeed, with the feedback on, the spectrum of the first coherent single-bunch modes is shown in Fig. 4. We can see that the beam is now stable beyond $N_p \simeq 3 \times 10^{11}$.

A positive chromaticity also has a beneficial effect when we include the beam-beam effects. Indeed, the beam-beam interaction with a large Piwinski angle and the beamstrahlung strongly affect the beam dynamics [27] and are

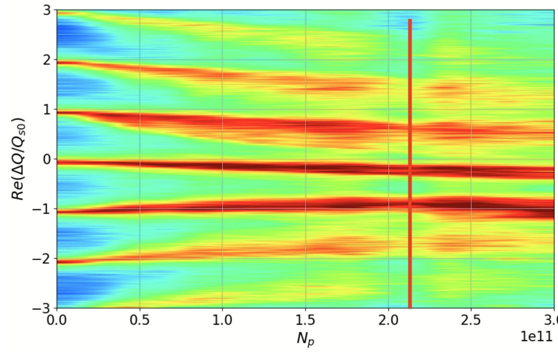

Figure 4: Real part of the normalized tune shift of the first azimuthal transverse coherent oscillation modes vs bunch population with, $Q'_{y,x} = 5$ and a feedback system.

affected by the wakefields: stable tune regions can be shifted and reduced in width [12, 28]. In Fig. 5, self-consistent simulations show the luminosity per IP versus the horizontal tune at a fixed vertical tune of 0.61: by properly choosing the collider working points and exploiting the positive chromaticity, a luminosity close to the nominal value of 141×10^{34} cm^{-2}s^{-1} can be achieved.

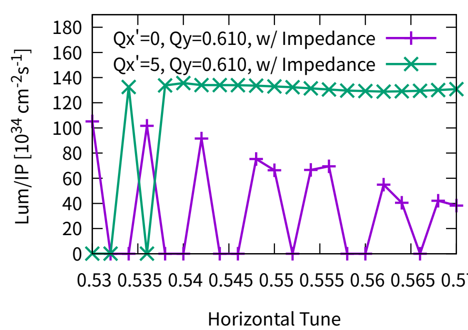

Figure 5: Luminosity versus horizontal tune at different chromaticities.

CONCLUSIONS

This paper reviews the TMCI excited by the updated impedance of the FCC-ee collider. A reduced beam pipe radius has lowered the instability threshold well below the single bunch nominal population compared to the previous results discussed in [13]. If not cured, it causes the beam to be lost, and some mitigation solutions have been investigated. Without the beam-beam interaction, TMCI can be mitigated with a bunch-by-bunch feedback system, necessary for damping the transverse coupled bunch instabilities, in combination with a positive chromaticity. Still, it could give rise to the -1 mode instability, and further investigation is necessary by simulating a more realistic feedback system. In collision, the transverse instability can be suppressed by exploiting the positive chromaticity even without using the feedback systems.

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