MITIGATION OF THE IMPEDANCE-RELATED COLLECTIVE EFFECTS IN FCC-EE*

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Abstract

In order to achieve a high luminosity in the electron-positron Future Circular Collider (FCC-ee), very intense multi-bunch beams with low emittances are accumulated in two separate rings and collide in two interaction regions exploiting the crab waist collision scheme. In order to preserve beam quality and to avoid collider performance degradation a careful study of beam collective effects is required. In this paper we overview impedance related coherent beam effects and instabilities potentially dangerous for FCC-ee and discuss measures and techniques for their mitigation.

INTRODUCTION

In order to ensure the future worldwide particle physics program, CERN has launched the Future Circular Collider (FCC) study for the design of different circular colliders for the post-LHC era [1–4]. A high luminosity electron–positron collider FCC-ee (former TLEP [5]) is considered as a potential first collider option to cover the beam energy range from 45.6 GeV to 182.5 GeV, thus to allow studying the properties of the Higgs, W and Z bosons and top quark pair production threshold with unprecedented precision. For example, the design luminosity of $2.3{\times}10^{36}$ $cm^{-2}s^{-1}$ at the Z resonance (45.6 GeV/beam) is by almost five orders of magnitude higher than the maximum luminosity ever achieved at LEP at the same energy (See Table 2 in [6]). There are several main ingredients that help reaching the high luminosities in FCC-ee: the two separate rings allow colliding many bunches without their parasitic interaction; the longer circumference allows storing higher beam intensities with the same synchrotron radiation loss; the crab waist collision scheme proposed [7, 8] and successfully tested at LNF INFN [9] makes it possible to reduce drastically the beta functions at the interaction points, to collide beams with much lower emittances and to suppress nonlinear resonances induced by the beam-beam interaction [10].

As it can be seen from Table 1 the beam emittances of FCC-ee are very small, comparable to those of the modern synchrotron light sources, while the beam stored currents are close to the best current values achieved in the last generation of particle factories (see Table 2 in [11] for comparison). Therefore, a careful study of collective effects is required in order to preserve the quality of the intense beams, to suppress eventual beam instabilities and to avoid excessive RF power losses leading to a damage of vacuum chamber components and accelerator hardware.

In this paper we present a preliminary study of the collective effects in FCC-ee and discuss eventual measures for their mitigation. A particular focus is given to the vacuum chamber impedance and impedance related instabilities.

Below we will consider only the Z resonance option since it is more vulnerable to the collective effects and instabilities because of the lower beam energy, longer damping times, higher beam intensities and highest number of bunches.

BEAM COUPLING IMPEDANCE AND ITS MINIMIZATION

As it has been shown in [12], for the 100 km long collider the vacuum chamber size, shape and material conductivity is of crucial importance for beam dynamics and, respectively, for collider design solutions and parameters choice. First of all, it has been decided to use the vacuum chamber with a round cross section in order to avoid the betatron tune variation with beam current in multi-bunch operations due to the qudrupolar resistive wall (RW) wake fields [13, 14]. It has been estimated that for a rectangular vacuum chamber made of copper and having the transverse sizes 70x120 mm^2 the tune shift would be as high as 0.4 for the nominal beam current of 1.4 A. The beam pipe radius of 35 mm has been chosen for FCC-ee as a reasonable compromise between the beam impedance and the power required for magnet power supplies.

Actually the shape of the beam pipe is not totally round but additional antechambers (winglets) are foreseen for pumping purposes and installation of synchrotron radiation (SR) absorbers, similarly to SuperKEKB design [15]. In addition, the antechambers are very helpful in suppression of the electron cloud effects in the positron ring.

In order to reduce the impedance it is desirable to avoid using multiple transitions in the vacuum chamber cross-section. For this reason the FCC-ee twin dipole and quadrupole magnets are designed in such a way to incorporate the beam pipe with the chosen geometry [16]. Fig. 1 shows a CAD model of a 1 m long section with the twin-bore magnets,

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Parameter	Z	W	H	ttbar	ttbar
Circumference *C* [km]	97.75	97.75	97.75	97.75	97.75
Energy *E* [GeV]	45.6	80	120	175	182.5
Number of bunches/beam	16640	2000	328	59	49
Bunch population *Np* [1.0e11]	1.7	1.5	1.8	2.2	2.3
Beam current *I* [mA]	1390	147	29	6.4	5.4
SR*energy loss per turn [GeV]	0.036	0.34	1.72	7.8	9.21
Bunch length with SR/BS*, σz [mm]	3.5/12.1	3.0/6.0	3.15/5.3	2.75/3.82	1.97/2.54
Bunch energy spread, SR/BS [%]	0.038/0.132	0.066/0.131	0.099/0.165	0.144/0.196	0.150/0.192
Longitudinal damping time [turns]	1281	235	70	23.1	20
Horizontal emittance, εx [nm]	0.27	0.84	0.63	1.34	1.46
Vertical emittance, εy [pm]	1.0	1.7	1.3	2.7	2.9
Luminosity per IP [1.0e34, cm-2s-1]	230	28	8.5	1.8	1.55

Table 1: Relevant FCC-ee baseline parameters. * SR: synchrotron radiation, BS: beamstrahlung.

the inserted vacuum chambers and pumping ports for localized pumps [17]. Furthermore, it is being considered using the “comb-type” technology in design of bellows and gate valves [18] with the RF shields fitting the vacuum chamber shape thus providing an electromagnetic continuity. As shown in Fig. 2, the BPM buttons positions are also chosen to fit this vacuum pipe geometry [17].

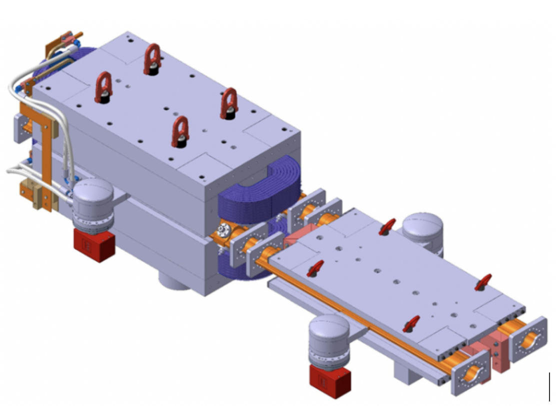

Figure 1: CAD model of the FCC-ee vacuum chamber with installed twin-bore magnets and attached pumping ports.

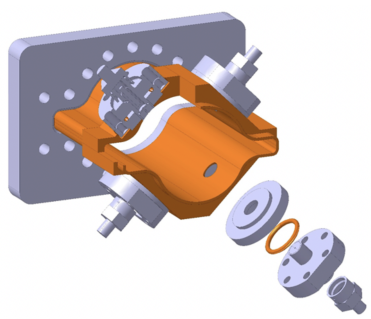

Figure 2: An extended view of one BPM block with button electrodes.

The FCC-ee vacuum chambers have to be coated in order to mitigate the electron cloud effects (beam induced multipacting) in the positron ring and/or to improve the vacuum pumping in both rings. Thin layers of NEG, TiN and AC have been considered for these purposes [19]. It has been demonstrated [12] that under certain assumptions, that are valid for the FCC-ee parameters, the longitudinal and transverse impedances of a two-layer beam pipe are given by the sum of two terms, the first term representing the well-known impedance of a single layer beam pipe and the second one describing an inductive perturbation proportional to the thickness Δ of the coating:

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

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

where Z_0 is the vacuum impedance, c the speed of light, b the pipe radius, δ_1, σ_1 and δ_2, σ_2 the skin depths and conductivities of the coating and the beam pipe (substrate), respectively.

As it can be seen, for the above assumptions, the real part of the impedance does not depend on the coating thickness and conductivity. The performed numerical studies [12] have confirmed that the resulting RF power losses due to the RW impedance remain almost unchanged for the coating conductivity and thickness varying in a very wide range. In turn, since the perturbation of the imaginary part due to the coating is proportional to its thickness and to the term $(1-\sigma_1/\sigma_2)$, if the coating conductivity is much smaller than the beam pipe material conductivity the impedance depends only on the thickness of the coating layer. On the other hand, if the two conductivities are comparable, this term reduces the coating perturbation. It has been shown that the coating thickness plays a crucial role affecting both single and multibunch beam dynamics [12]. In particular, in order to keep longitudinal microwave instability under control the coating thickness should be as small as 50-100 nm [20]. For this reason, a campaign of dedicated measurements has been launched to to study the properties of NEG thin films with thickness below 250 nm [20,21], such as secondary emission yield and activation performance.

In addition to the RW impedance there are many other impedance sources in the machine. The design of the vacuum chamber components such as RF cavities, kickers, beam position monitors (BPMs), bellows, flanges etc. has not been finalized yet. In order to evaluate their possible impedance contribution, the present strategy consists in adopting the best design solutions of the accelerator components used in the modern synchrotron light sources and the particle factories. These are, for example, comb-like bellows, gate valves and flanges used in SuperKEKB [22], the DAΦNE longitudinal feedback kickers [23] and injection kickers [24], SIRIUS conical beam position monitors [25] etc. The work is ongoing in order to decrease the FCC-ee interaction region impedance and to suppress eventual trapped higher modes (HOM) in the area where the two ring beam pipes merge (Y-chamber) [26], see Fig. 3.

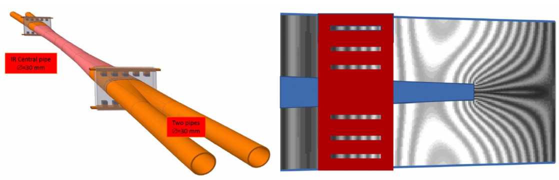

Figure 3: The interaction region Y-chamber with the installed HOM suppressors (see details in [26]).

Special efforts are being dedicated to design the RF cavities with HOM couplers in such a way to keep the HOM parameters under a harmless level [27,28].

For the present impedance model we consider that for running at Z energy the RF system will consist of 56 single cell cavities operating at 400 MHz [29] and arranged in groups of four cavities connected to the beam pipe by 0.5 m long tapers. In order to eliminate the beam halo and to suppress the background, collimators based on PEP-II and SuperKEKB design [30,31] 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 SR has been minimized by placing them inside the two rectangular antechambers on both sides of the beam pipe. This model also includes 4000 BPMs [25] and 8000 comb-type bellows with RF shielding [32] to be allocated before and after each BPM. The impedance contribution of the absorbers "hidden" inside the antechambers is almost negligible with respect to the contributions of the other vacuum chamber components.

The coupling impedances and wake fields for these vacuum chamber elements have been evaluated numerically [21]. Figure 4 shows the longitudinal wake potentials of each component for the nominal bunch length of 3.5 mm. Table 2 summarizes the corresponding loss factors. As it can be seen, the resistive walls with 100 nm coating provide the dominating contribution in both the total wake potential

Component	Number	k_{loss} [V/pC]	P_{loss} [MW]
Resistive walls	97.75 km	210	7.95
RF cavities	56	18.46	0.7
RF double tapers	14	6.12	0.23
Collimators	20	38.36	1.45
Beam position monitors	4000	31.47	1.19
Bellows with RF shielding	8000	49.01	1.85
Total		**353.4**	**13.4**

Table 2: RF power losses due to different vacuum chamber components

and respective power losses that are not negligible compared with the 50 MW power lost by SR. Hopefully, the power losses are expected to be substantially lower due to the bunch lengthening.

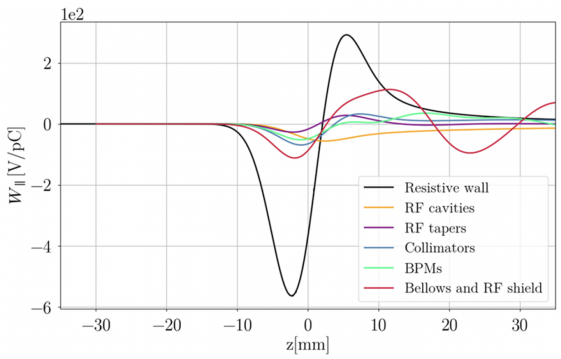

Figure 4: Longitudinal wake potential of different vacuum chamber components calculated for 3.5 mm Gaussian bunch. The resistive wall potential is plotted for 100 nm thin coating.

IMPEDANCE RELATED EFFECTS AND INSTABILITIES

The electromagnetic beam interaction with a surrounding vacuum chamber, described in terms of wake fields and impedances, affects longitudinal and transverse beam dynamics. It can result in both single and multi-bunch instabilities and overheating of vacuum chamber components. The impedance related collective effects can substantially worsen the overall collider performance.

As it has been shown in [12] the resistive walls give the dominating contribution to the impedance budget of FCC-ee. The resistive wall impedance alone causes a substantial bunch lengthening and bunch shape distortion as shown in Fig. 5, compared to the unperturbed Gaussian bunch (dashed line in the right-hand side of the figure).

The left plot in Fig. 5 shows the rms bunch length as a function of bunch intensity for different thickness of the vacuum chamber coating while the right picture demonstrates the bunch profile distortion for the nominal bunch intensity [12].

In collisions with a large Piwinski angle, as is the case of FCC-ee, the collider geometric luminosity decreases for longer bunches. On the other hand, for longer bunches

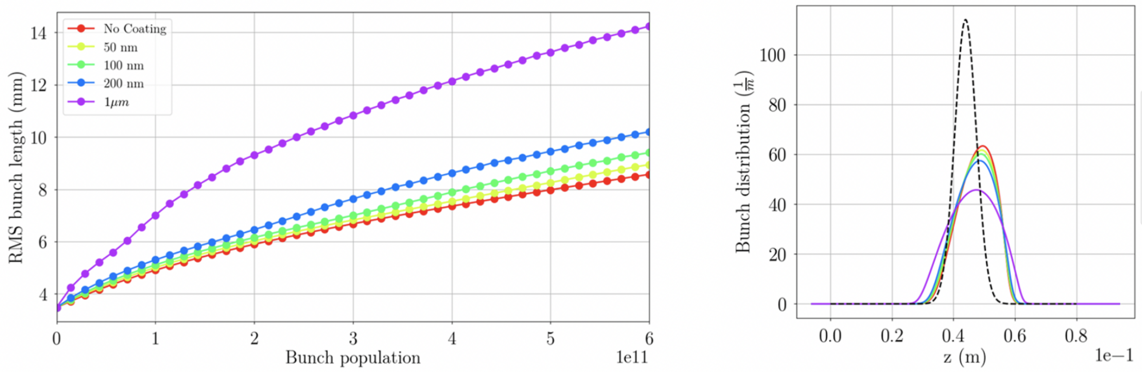

Figure 5: Bunch lengthening (left picture) and bunch shape distortion (right pictures) calculated for different coating thicknesses. The dashed line in the right figure is the unperturbed zero current Gaussian bunch.

the beam lifetime increases and the RF power losses are reduced. However, at certain bunch intensity, microwave instability can take place. Typically the microwave instability does not produce a bunch loss, but the consequent energy spread growth and possible bunch internal oscillations above the instability threshold cannot be counteracted by a feedback system. In addition, the longitudinal wake fields result in the synchrotron tune reduction and a large incoherent synchrotron tune spread. Both these effects influence beam-beam performance shifting the collider working point and affecting the coherent and incoherent beam-beam resonances.

Figure 6 shows the energy spread versus bunch intensity for different values of vacuum chamber coating thickness (left plot) and the synchrotron tune shift and spread calculated for the 100 nm coating thickness (right plot).

As it is seen in Fig. 5 and Fig. 6, in order to avoid the excessive bunch lengthening and, even more important, to stay below the microwave instability threshold the coating thickness should be smaller than 200 nm. This request has resulted in dedicated studies of thin TiZrV films properties for the film thickness below 250 nm [21].

Including the impedance contributions of the other vacuum chamber components does not change the results drastically. The left plots in Fig. 7 show the bunch length in FCC-ee as a function of the bunch population, while the right plots indicate the respective energy spread calculated using the wake potential shown in Fig. 4. The blue curves correspond to the bunch length and energy spread variations for non-colliding bunches. At the nominal intensity the bunch lengthens till about 7 mm, while the microwave instability threshold is by about a factor of 1.5 higher than the nominal bunch population. So there is only a small margin left for eventual impedance increase. In collision, the “beamstrahlung” effect [33] results in an additional energy spread increase leading to the strong bunch elongation and the microwave instability threshold increase beyond the considered bunch intensities (brown curves).

Differently from the longitudinal microwave instability, the transverse mode coupling instability (TMCI) is destructive for intense bunches. The bunches can be lost in few revolution turns. The instability takes place when coherent frequencies of different modes of transverse internal bunch oscillations merge. The TMCI threshold has been evaluated with the analytical Vlasov solver DELPHI [34] by considering the dominating RW impedance and by taking into account the bunch lengthening due to the longitudinal wake fields shown in Fig. 7. It has been found that in the transverse case the TMCI instability threshold is affected to a lesser extent by the coating thickness due to the bunch lengthening effect. For comparison, Fig. 8 shows the real part of the frequency shift of the first coherent oscillation modes as a function of the bunch population for 50 nm (left) and 1 μm coatings (right), respectively. The dashed line represents the nominal bunch intensity. The TMCI threshold (merging lines) is about a factor 2.5 higher than the nominal intensity.

Analyzing the multi-bunch beam dynamics it has been found that the coupled bunch instability due to the transverse RW long range wake fields is another critical issue for the collider [12]. The growth rate of the fastest coupled bunch mode is estimated to be 435 1/s corresponding to about 7 revolution turns. It is worth noting here that the transverse radiation damping time is 2550 turns, i.e. it is much longer than required for the instability suppression. So a robust feedback system is necessary to mitigate the fast instability. As a possible solution it has been proposed to use a distributed feedback system. A dedicated study is underway to develop such a challenging system [35].

The longitudinal radiation damping alone also cannot suppress the longitudinal coupled bunch instabilities due to the beam interaction with parasitic higher order modes (HOM) trapped in the vacuum chamber components. In order to cope with the instabilities special HOM damping techniques are to be applied to reduce the shunt impedances of the HOM to a harmless level, as discussed in [36]. In addition, also in this case a longitudinal feedback system has to be developed as a further safety knob.

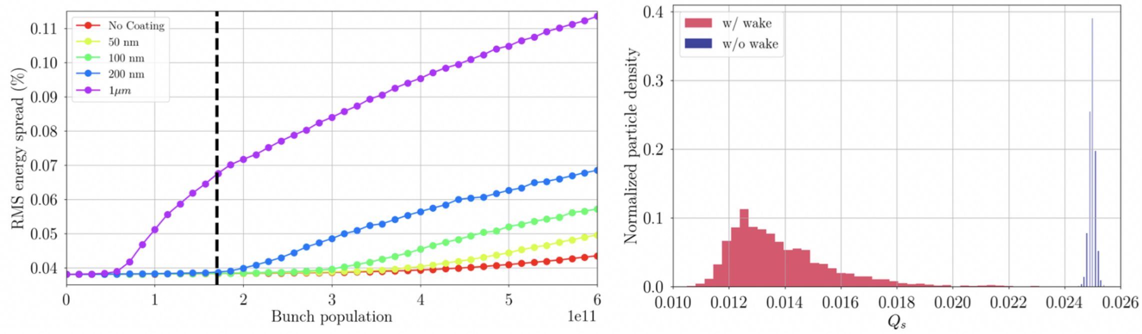

Figure 6: Rms energy spread as a function of the bunch intensity (left picture) and the synchrotron frequency distribution at the nominal bunch current calculated for the coating thickness of 100 nm (right picture).

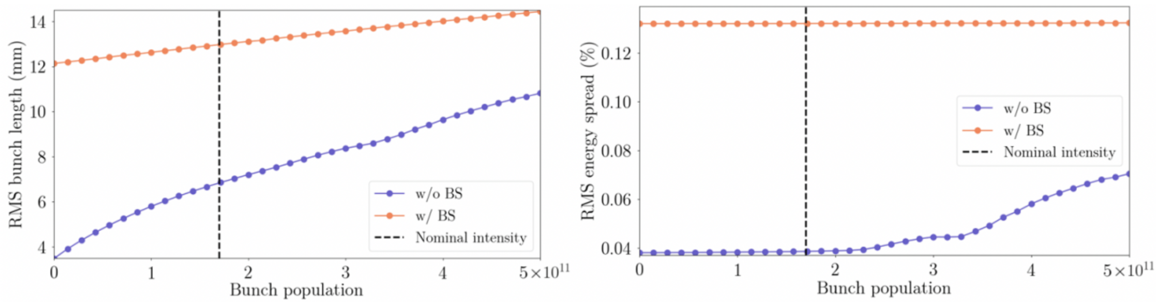

Figure 7: Bunch lengthening (left picture) and the energy spread (right picture) in FCC-ee as a function of the bunch intensity.

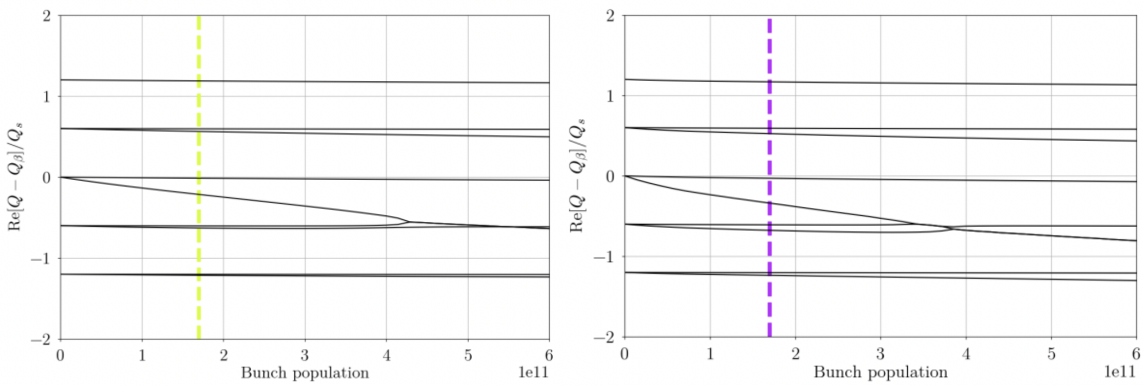

Figure 8: Real part of the frequency shift of the first transverse coherent oscillation modes for 50 nm (left) and 1 μm (right) coating thickness.

CONCLUSIONS

FCC-ee beam coupling impedance and related collective effects play an important role for both the parameters choice and design solutions for the 100 km collider. The work is in progress in order to minimize the impedance and to mitigate the related instabilities. The shape of the vacuum chamber pipe was chosen to be similar to that used in SuperKEKB: the round shape should help minimizing the eventual betatron tune shift due to the quadrupolar resistive wall wake fields, while the attached winglets (small antechambers) will be used to install "hidden" absorbers and to connect the pumping ports. In order to avoid using multiple tapers it has been decided to keep the same chamber cross-section all around the ring, in the arcs and straight sections. Moreover, bellows, gate valves, flanges and BPM blocks are being designed in such a way to fit the vacuum pipe shape. The beam dynamics analysis has shown that the pipe coating should be as thin as possible in order to mitigate the impact of the resistive wall impedance. Respectively, a dedicated program has been launched at CERN in order to study the properties of thin TiZeV films. The low impedance vacuum chamber component design will rely on the experience gained during design and commissioning phases of other high intensity particle colliders and modern sources of synchrotron radiation. A particular care now is given to reduce the impedance and to eliminate trapped higher order modes in the FCC-ee interactions region. An optimization of the RF cavity HOM couplers is under way in order to keep the HOM parameters under a harmless level. Since the estimated growth time of the couple bunch instabilities is compared to a few revolutions turns a proposal of using a distributed feedback system has been endorsed and is under study. The work will continue to keep both single and multi-bunch effects and instabilities in FCC-ee under control.

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REFERENCES

[1] FCC Collaboration, "FCC Physics Opportunities: Future Circular Collider Conceptual Design Report Volume 1", Eur.Phys.J. C79 (2019) no.6, 474. DOI:10.1140/epjc/s10052-019-6904-3.

[2] FCC Collaboration, "FCC-ee: The Lepton Collider: Future Circular Collider Conceptual Design Report Volume 2", Eur.Phys.J.ST 228 (2019) no.2, 261-623. DOI:10.1140/epjst/e2019-900045-4

[3] FCC Collaboration, "FCC-hh: The Hadron Collider: Future Circular Collider Conceptual Design Report Volume 3", Eur.Phys.J.ST 228 (2019) no.4, 755-1107. DOI:10.1140/epjst/e2019-900087-0

[4] FCC Collaboration, "HE-LHC: The High-Energy Large Hadron Collider", Eur.Phys.J.ST 228 (2019) no.5, 1109-1382. DOI:10.1140/epjst/e2019-900088-6

[5] M.Bicer at al., "First look at the physics case of TLEP", JHEP 1401 (2014) 164. DOI: 10.1007/JHEP01(2014)164

[6] R. Assmann, M. Lamont, and S. Myers, "A brief history of the LEP collider", Nucl. Phys. B Proc. Suppl., Vol. 109, pp. 17-31, 2002. DOI:10.1016/S0920-5632(02)90005-8

[7] P. Raimondi, "Status on SuperB effort", talk at the 2nd SuperB Workshop, Frascati, Italy, 2006.

[8] P. Raimondi, D. Shatilov, and M. Zobov, "Beam-beam issues for colliding schemes with Large Piwinski angle and crabbed waist", Rep. LNF-07-003-IR, e-Print: physics/0702033, Feb. 2007.

[9] M. Zobov et al., "Test of crab waist collisions at DAΦNE Phi-factory", Phys. Rev. Lett., Vol. 104, p. 114801, Apr. 2010. DOI: 10.1103/PhysRevLett.104.174801

[10] D. Shatilov, E. Levichev, E. Simonov, and M. Zobov, "Application of frequency map analysis to beam-beam effects study in crab waist collision scheme", Phys. Rev. ST Accel. Beams, Vol.14, p. 014001, Jan. 2011. DOI: 10.1103/PhysRevSTAB.14.014001

[11] M. Zobov, "Next generation of electron-positron factories", Phys. Part. Nucl., Vol. 42, pp-799. 782, 2011. DOI: 10.1134/S1063779611050066

[12] 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, Apr. 2018. doi: 10.1103/PhysRevAccelBeams.21.041001

[13] A. Chao, S. Heifets, and B. Zotter, "Tune shifts of bunch trains due to resistive vacuum chambers without circular symmetry", Phys. Rev. ST Accel. Beams, Vol. 5, p. 111001, 2002. doi: 10.1103/PhysRevSTAB.5.111001

[14] A. Blednykh et al., "Low-frequency quadrupole impedance of undulators and wigglers", Phys. Rev. Accel. Beams, Vol. 19, p. 104401, Oct. 2016. doi: 10.1103/PhysRevAccelBeams.19.104401

[15] Y. Suetsugu et al., "Design and construction of the SuperKEKB vacuum chamber", J. Vac. Sci. Tech. A, Vol.30, p. 031602, Mar. 2012. doi:10.1116/1.3696683

[16] A. Milanese, "Efficient twin aperture magnets for the future e+e- collider", Phys. Rev. Accel. Beams, Vol. 19, p. 112401, Nov. 2016. doi: 10.1103/PhysRevAccelBeams.19.112401

[17] C. Garion, and R. Kersevan, "Design of the vacuum system of the FCC-ee electron-positron collider", Proc. 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May 2019, pp. 1319-132. doi: 10.18429/JACoW-IPAC2019-TUPMP035

[18] Y. Suetsugu et al., "Development of bellows and gate valves with a comb-type rf shield for high current accelerators: four-year beam test at KEK B-factory", Rev. Sci. Instrum., Vol. 78, p. 043302, Apr. 2007. doi: 10.1063/1.2723747

[19] E. Belli et al., "Coupling impedance and collective effects for FCC-ee", Proc. 8th Int. Particle Accelerator Conf. (IPAC2017), Copenhagen, Denmark, May 2017, pp. 3734-3737. doi: 10.18429/JACoW-IPAC2017-THPAB020

[20] E. Belli et al., "Single bunch instabilities in FCC-ee", Proc. 9th Int. Particle Accelerator Conf. (IPAC2018), Vancouver, Canada, pp. 3336-3339, doi: 10.18429/JACoW-IPAC2018-THPAK052

[21] E. Belli et al., "Electron cloud buildup and impedance effects on beam dynamics in the Future Circular e+e- Collider and experimental characterization of thin TiZrV vacuum chamber coatings", Phys. Rev. Accel. Beams, Vol. 21, p. 111002, Nov. 2018. doi: 10.1103/PhysRevAccelBeams.21.111002

[22] K. Shibata et al., "Commissioning status of SuperKEKB vacuum system", Proc. 62th ICFA Advanced Beam Dynamics Workshop on High Luminosity e+e- Colliders (eeFACT2018), Hong Kong, China, pp. 226-233. doi: 10.18429/JACoW-eeFACT2018-WEOAB01.

[23] R. Boni et al., "A waveguide overloaded cavity as longitudinal kicker for DAϕNE bunch-by-bunch feedback system", Part. Accel., Vol. 52, pp. 95-113, Dec. 1995.

[24] D. Alesini et al., "Design, test, and operation of new tapered strip-line injection kickers for the e+e- collider DAϕNE", Phys. Rev. Accel. Beams, Vol. 13, p. 111002, 2010. doi10.1103/PhysRevSTAB.13.111002

[25] H.O.C. Duarte, L. Sanfelici, and S.R.Marques, "Design and impedance optimization of the SIRIUS BPM button", Proc. IBIC2013, Oxford, UK, 2013, pp. 365-368.

[26] A. Novokhatski et al., "Unavoidable trapped mode in the interaction region of colliding beams", Phys. Rev. Accel. Beams, Vol. 11, p. 111005, Nov. 2017. doi: 10.1103/PhysRevAccel-Beams.20.111005

[27] S.G. Zadeh, “HOM damping design studies for FCC-ee cavities”, presentation at FCC Week 2019, Brussels, Belgium, Jun. 2019. https://indico.cern.ch/event/727555/contributions/3436401/

[28] S. Gorgi Zadeh, T. Flisgen, R.Calaga and U. van Rienen, HOM damping options for the Z-Pole operating scenario of FCC-ee, Journal of Physics: Conference Series, 2019, doi:10.1088/1742-6596/1350/1/012007

[29] A. Butterworth, “Cavity design and beam-cavity interaction challenges”, presentation at FCC Week 2017, Berlin, Germany. https://indico.cern.ch/event/556692/contributions/2484361/

[30] S. DeBarger et al., “The PEP-II movable collimators”, Preprint SLAC-PUB-11752, 2001.

[31] T. Ishibashi, S. Terui, and Y. Suetsugu, “Low impedance movable collimators for SuperKEKB”, Proc. 8th Int. Particle Accelerator Conf., Copenhagen, Denmark, pp. 2929-2932. doi: 10.18429/JACoW-IPAC2017-WEPIK009

[32] Y. Suetsugu, M. Shirai, and K. Shibata, “Possibility of comb-type shield structure for high current accelerators”, Phys. Rev. Accel. Beams, Vol. 6, p. 103201, Dec. 2003. doi: 10.1103/PhysRevSTAB.6.103201

[33] D. Leshenok, S. Nikitin, and M. Zobov, “Model to study interplay between beamstrahlung and coupling impedance in future lepton colliders”, e-Print: 2004.02553, Apr.2020.

[34] https://twiki.cern.ch/twiki/bin/view/ABPComputing/DELPHI

[35] A.Drago, “Feedback systems for FCC-ee”, Proc. 58th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders, 24-27 October 2016, Daresbury, United Kingdom, pp. 136-142. doi: 10.18429/JACoW-eeFACT2016-TUT3AH9

[36] E.Belli et al., “Single beam collective effects in FCC-ee due to beam coupling impedance”, e-Print: 1609.03495, Sep. 2016.