ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB392

CONCEPTUAL DESIGN OF THE VACUUM SYSTEM FOR THE FUTURE CIRCULAR COLLIDER FCC-ee MAIN RINGS

R. Kersevan†, C. Garion, CERN, Geneva, Switzerland

Abstract

The Future Circular Collider study program comprises several machine concepts for the future of high-energy particle physics. Among them there is a twin-ring e-e+ collider capable to run at beam energies between 45.6 and 182.5 GeV, i.e. the energies corresponding to the resonances of the Z, W, H bosons and the top quark. The conceptual design of the two 100-km rings has advanced to what is believed to be a working solution, i.e. capability to deal with low-energy (45.6 GeV) high-current (1390 mA) version as well as the high-energy (182.5 GeV) low-current (5.4 mA) one, with intermediate energy and current steps for the other 2 resonances. The limit for all the versions is given by the 50 MW/beam allotted to the synchrotron radiation (SR) losses. The paper will outline the main beam/machine parameters, the vacuum requirements, and the choices made concerning the vacuum chamber geometry, material, surface treatments, pumping system, and the related pressure profiles. The location of lumped SR photon absorbers for the generic arc cell has been determined.

MACHINE AND VACUUM PARAMETERS

All FCC-ee machine versions generate a copious flux of SR, in particular the low-energy high-current one. The relevant machine and vacuum parameters are listed in Table 1 [1]. The dynamic gas load is calculated assuming a customary value for the photo-desorption rate of $1\cdot10^{-6}$ molecules/ph, and it is proportional to the photon flux. The critical energy of the SR spectrum of each machine, for the arc dipoles, is 19.5, 105.5, 356.2, and 1253.1 keV, respectively. Only for the low-energy version the critical energy is well below the Compton edge for copper or aluminium (100~200 keV), the candidate vacuum materials. The dynamic gas load Q' in Table 1 does not include the contribution from Compton photons scattering back into the vacuum chamber and generating additional gas load. This effect had been observed in the LEP collider when the energy had been raised above 45 GeV [2]. This additional gas load will be evaluated in the future, once the design of the vacuum system is finalized, as it depends on choices related to the vacuum chamber and magnets materials and shielding arrangements for minimizing high-energy, large-angle Compton photon background scattering towards machine and tunnel equipment [3]. We also neglect any gas load contribution coming from either electron cloud (EC) in the e+ ring or ion-desorption in the e- ring, as we assume that these effects will be properly mitigated either via surface treatments given by low secondary electron yield (SEY) thin-films or surface textures (e.g. laser-ablation). We make use here of the results of the previous Horizon 2020-funded R&D program for the FCC-hh machine, where both laser-ablated and amorphous-carbon coatings were tested [4, 5]. All machine versions will have to absorb and dissipate efficiently the same amount of SR power, 50 MW.

Table 1: Machine and Vacuum Parameters

Beam Energy E (GeV)	Beam Current I (mA)	Photon Flux F'(ph/s/m)	Dynamic Gas Load Q'(mbar·l/s/m)
45.6	1390	$7.17\cdot10^{17}$	$2.90\cdot10^{-8}$
80	147	$1.38\cdot10^{17}$	$5.58\cdot10^{-9}$
120	29	$4.13\cdot10^{16}$	$1.67\cdot10^{-9}$
182.5	5.4	$1.18\cdot10^{16}$	$4.78\cdot10^{-10}$

VACUUM REQUIREMENTS

The average vacuum pressure along the beam path must be low enough so that the beam-gas scattering lifetime is bigger than the lifetime given by the collision and scattering rates at the interaction points. We assume that the accelerator will be conditioned when the average pressure will be in the low 10^{-9} mbar range, e.g. $2\cdot10^{-9}$. For the dynamic gas load Q' listed in Table 1, this requirement corresponds to having an effective linear pumping speed of 14.5, 2.8, 0.84, and 0.24 l/s/m, respectively. The research program of the FCC-ee machine foresees to start at the lowest energy, spending 4 years at that energy, and then increasing the energy in steps (see Fig. 3, in [1]). At each energy increase several additional RF cavities will be installed, in order to balance the energy losses per turn due to SR, which scale as the beam energy to the fourth power (see Fig. 4 in [1]). For practical and economic reasons, the vacuum system of the machines should not be modified much in the long arcs, if at all, when the beam energy is changed. This means that the vacuum conditioning at the lowest energy will be the most important factor assuring a sufficiently low pressure also at the following, higher energies. Another requirement is that the initial conditioning be as quick as possible, so that a maximum of integrated luminosity at the corresponding Z-boson resonance can be accumulated. Because of this, the vacuum system must be designed so that it provides the required pumping speed and a fast conditioning for the Z resonance.

VACUUM SYSTEM

Vacuum Chambers

The FCC-ee machines are high-luminosity, low-emittance colliders, very sensitive to any disturbances and

† Reporting for the Vacuum Surfaces and Coatings Group, Technology Department, CERN; roberto.kersevan@cern.ch

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB392

beam degradations related to beam impedance contributions, such as resistive wall and geometric one. For the former we have chosen copper alloy as the primary material, since it also guarantees a good thermal conductivity and low electrical resistivity. The geometric impedance contribution is dealt with by designing all the changes of cross-section with smooth transitions and tapers. The preference for copper alloys as vacuum chamber material comes also from the need to have some shielding for the X-ray SR fan, and minimize the irradiation of machine and tunnel components [3].

The chosen cross-section in the arc regions is shown in Fig. 1, where its integration within the proposed two-in-one arc quadrupole yoke is shown [6].

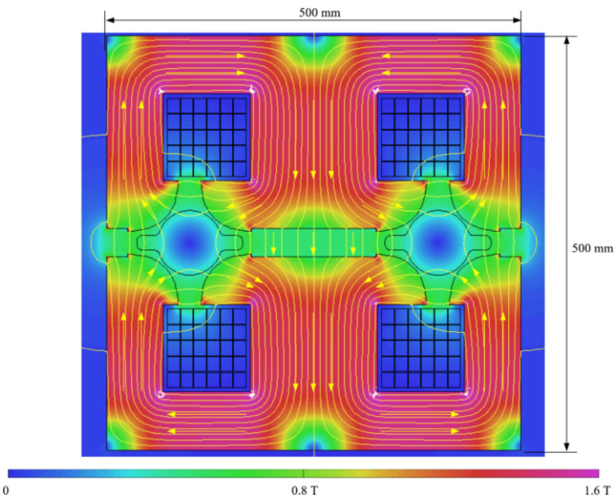

Figure 1: Two-in-one quadrupole magnet with cross-sections of the two vacuum chambers.

The vacuum chamber cross-section is made up of a 2 mm-thick, 70 mm internal diameter (ID) circular tube with two "winglets" placed on each side of the circle, on the plane of the orbit. The overall internal width is 120 mm. This solution is like the one adopted for the SuperKEKB collider. Contrary to SuperKEKB, we plan to use the winglet on the external side of each ring, i.e. where the SR fan of each beam would go, to locate a number of lumped SR absorbers, similar to what is done for SR light sources, see Fig. 2. With an average distance among consecutive absorbers of about 5.8 m, all the primary SR photon fan can be intercepted. The corresponding average SR power they absorb is 4.1 kW over a vertically narrow strip ~120 mm-long, the average arc dipole linear SR power density being 730 W/m. This level of power is like that commonly dealt with in SR light sources, and therefore can be considered an item with not much need for R&D efforts.

Raytracing Simulations

Many raytracing montecarlo simulations have been carried out using the codes SYNRAD+ and Molflow+ [7]. We have created a detailed 3D model for a representative 140 m-long section of the FCC-ee arc, for both beams, and using the corresponding up-to-date lattice files we have determined the optimal position for each of 25 SR absorbers per ring. The 140 m-long model has 5 dipoles and 5 quadrupoles, interleaved, and the beam size and angular divergence at each point of the orbits are generated by SYNRAD+ using the lattice functions.

In a first run, it is assumed that the walls of the chamber and of the absorbers have photon reflectivity equal to zero. Like this, we can find the optimal position of each of the 25 absorbers along the beam path, sequentially, one beam at a time. Due to vertical size limitations in the gap of the quadrupoles' and sextupoles' yokes and coils, we have avoided installing any SR absorbers at locations where quadrupoles and sextupoles will be placed.

In a second set of SYNRAD+ runs, we have set the reflectivity of the vacuum chamber and SR absorbers' surfaces as per data in literature, i.e. with material-, energy-, and angle-dependent reflectivity [8]. This exercise has allowed us to determine that the tapered 300 mm-long SR absorbers will need to have the surface hit by the primary SR photons along a V-shaped geometry, in order to decrease the surface SR power density, which for the 182.5 GeV version of the machine would be too high were it to impinge on a flat surface. This kind of geometry is exploited usually in SR light sources and should not constitute a major problem to design, and it will be prototyped and tested.

The second set of SYNRAD+ runs, with realistic photon reflectivity, allows us to determine the distribution of scattered photons, and to get a mapping of their surface density. This is important for our colleagues who deal with the EC issues, and to determine the number of primary photo-electron density, which could affect the beam stability.

After this phase of raytracing and optimization of the position of the absorbers with SYNRAD+, we can use the test-particle montecarlo code Molflow+ to simulate the SR photon-induced outgassing and the relevant pressure profiles, using SYNRAD+'s results as input, as done in [8].

The 3D model for Molflow+ assumes that either in front or on the side of each SR absorber there may be one pumping dome, connected to the vacuum chamber via 125 mm-long slots machined on the wall of the winglet, as indicated in Fig. 2.

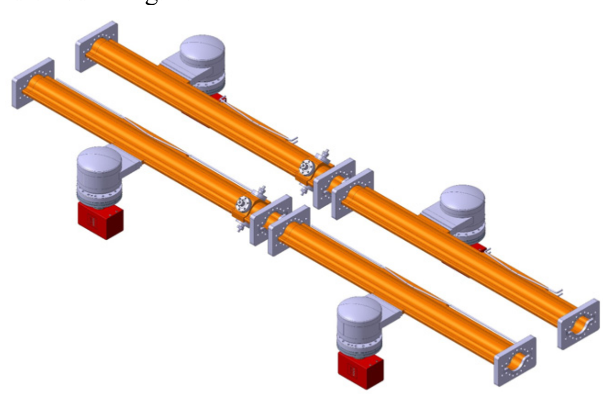

Figure 2: Schematics of two dipole and two quadrupole vacuum chambers (with BPM buttons) for the two rings, with 4 representative pumping domes equipped with NEG-pumps.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB392

Pumping Arrangement

In Fig. 2 the external beam is on the right: it has SR absorbers and the pumping domes on the same side, while the internal beam has the SR absorbers facing the pumping domes. Rectangular flanges like those developed for the SuperKEKB collider have been proposed, Matsumoto-Ohtsuka-type [9], because regular Conflat flanges would exceed the space available between magnets.

The Molflow+ simulations have shown that there is no need to install one pump near each absorber, in order to get a sufficiently low pressure. In fact, the FCC-ee arcs are ~80 km long, each ring, and placing one pump every 5.8 m average distance would mean almost 14,000 pumps per ring, which is unreasonable, and would also be too expensive. We still must determine the optimal length of the vacuum sectors, which for the LEP machine were ~200 m-long [2]. We could possibly have 4 to 6 pumping domes per vacuum sector, i.e. one pump every 33 to 50 m on average. Most of the pumping speed would be given by non-evaporable getter (NEG) coating thin films, based also on extensive in-house experience, see next section.

Surface Treatments

For the positron beam to avoid suffering from EC issues, and for the electron beam to avoid suffering from ion-instabilities, some form of surface treatment or special geometry must be envisaged. We have chosen this solution to obtain a low SEY for taking care of the EC issues. This also guarantees a quick vacuum conditioning with low pressures and reduced beam-ionization-induced residual gas ion generation, avoiding ion-instabilities.

Without NEG-coating it would be very difficult to obtain the design values for beam-gas scattering lifetime, and stored current within the rather short timeframe envisaged in the Conceptual Design Report [1], 4 years for the Z-pole research program. Also, the number of pumps would need to be much higher, since with no NEG-coating and its distributed pumping speed we would get parabolic-like pressure profiles, due to the rather low specific conductance of the chosen vacuum chamber cross-section (~47 liter·m/s) [10].

NON-ARC SECTIONS

The analysis carried out so far concerned only the arc sections of the two main rings. An analysis and modelling using the two montecarlo codes SYNRAD+ and Molflow+ sequentially has also been carried out for the sensitive Machine Detector Interface (MDI) areas [10]. The vacuum chamber cross-section and pumping concepts, lumped pumps and NEG-coating, are the same as for the arc sections, only the spacing and arrangement of the SR absorbers is different. There is an anti-bend section immediately upstream of the MDI areas which requires some SR absorbers to be placed on both winglets, internally and externally.

CONCLUSIONS

We have briefly outlined the present status of the conceptual design of the vacuum system for the FCC-ee collider rings' arc sections. Extensive modelling efforts have allowed us to design a vacuum system which should be conditioned in a sufficiently fast time, compatible with the planning of the operation of the machine at the various energies. The next phase of Horizon 2020 funding should allow us to design, build, and test prototypes of relevant components, a detailed program is being studied at this time.

ACKNOWLEDGEMENTS

FCCIS: This project has received funding from the European Union's Horizon 2020 research and innovation programme under the European Union's Horizon 2020 research and innovation programme grant agreement No 951754.

REFERENCES

[1] A. Abada *et al.*, "FCC-ee: The Lepton Collider", *Europ. Phys. J. Special Topics*, vol. 228, pp. 261-623, 2019. doi:10.1140/epjst/e2019-900045-4

[2] J. C. Billy *et al.*, "The LEP vacuum system: A summary of 10 years of successful operation", in *Proc EPAC-2000*, Vienna, Austria, May 2000, paper THP1B14, pp. 2286-2288.

[3] F. Cerutti, "Status of radiation environment assessment in the FCC-hh and FCC-ee machines", *FCC Week 2019*, Brussels, Belgium, Jun. 2019,

[4] I. Bellafont *et al.*, "Design of the future circular hadron collider beam vacuum chamber", *Phys. Rev. Accel. Beams*, vol. 23, p. 033201, 2020. doi:10.1103/PhysRevAccelBeams.23.033201

[5] L. A. Gonzalez *et al.*, "Design of the future circular hadron collider beam vacuum chamber", *Phys. Rev. Accel. Beams*, vol. 22, p. 083201, 2019. doi:10.1103/PhysRevAccelBeams.22.083201

[6] J. Bauche, "Shift of twin-aperture magnetic axis with field strength", presented at the *129th FCC-ee Optics Design Meeting*, CERN, Geneva, Switzerland, Nov. 2020,

[7] Molflow+, CERN, https://molflow.web.cern.ch

[8] M. Ady, R. Kersevan, and M. J. Grabski, "Monte Carlo Simulations of Synchrotron Radiation and Vacuum Performance of the Max IV Light Source", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 2344-2347. doi:10.18429/JACoW-IPAC2014-WEPME037

[9] Y. Suetsugu *et al.*, "Application of a Matsumoto-Ohtsuka-type vacuum flange to beam ducts for future accelerators", *Journal Vacuum Science and Technology A*, vol. 23, no. 6, pp. 1721-1727, 2005. doi:10.10.1116/1.2101808

[10] R. Kersevan, "FCC-ee beam vacuum challenges, concepts and future R&D plans", *FCC Week 2019*, Brussels, Belgium, Jun. 2019.