CHALLENGES AND STATUS OF THE RAPID CYCLING TOP-UP BOOSTER FOR FCC-ee

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Abstract

FCC-ee is a 100 km e^+e^- collider, which is being designed within the Future Circular Collider Study (FCC) for precision studies and rare decay observations in the range of 90 to 350 GeV centre-of-mass energy. The beam lifetime will be limited to less than one hour, because of radiative Bhaba scattering and beamstrahlung. In order to keep the luminosity on the high level of 10^{35} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ continuous top-up injection is required. Therefore, besides the collider, that will operate at constant energy, a fast cycling booster synchrotron will be installed in the same tunnel. The injection energy to the booster synchrotron will be around 6-20 GeV. Such small energies together with the large bending radius not only create an ultra-small beam emittances, but also requires very low magnetic fields close to the limit of technical feasibility. This paper will focus on the challenges and requirements for the top-up booster design arising from low magnetic fields and collective instabilities and present the status of the lattice design.

INTRODUCTION

The lepton collider FCC-ee, which is being studied within the Future Circular Collider Study (FCC), is designed for high luminosity electron-positron collisions for precision measurements at centre-of-mass energies from 90 to 350 GeV. This energy range not only allows precision measurements of the Z and W bosons with unprecedented accuracy, but also of the Higgs boson and the top quark, which has not been done before. As a consequence of the aggressive interaction region parameters, the expected luminosity lifetime is limited by radiative Bhaba scattering and beamstrahlung to less than one hour [1]. Efficient operation therefore requires continuous top-up injection at full collision energy. A fast cycling booster synchrotron of approximately 100 km circumference will therefore be installed in the same tunnel as the main collider storage rings.

The preliminary injector chain is presented in [2] and [3] and is designed to allow continuous top-up injection on a 10 % level every 10-14 seconds. It comprises a 6 GeV linac, which will be used both for electrons and positrons, with a junction to an intermediate damping ring operated at the energy of 1.54 GeV. In order to increase the injection energy in the FCC-ee Booster from 6 GeV to 20 GeV the option of an additional pre-booster synchrotron with the length of 2.7 km is under investigation and discussed in [4].

LAYOUT AND LATTICE

As the FCC-ee Top-Up Booster will be housed in the same tunnel as the FCC-ee collider, it obviously has to follow its geometry. Figure 1 shows the layout of the FCC main tunnel, which is determined by technological requirements of the FCC hadron collider FCC-hh and geological aspects of the Geneva basin. The layout consists of short straight sections with the length of 1.4 km, which are clustered to groups of three connected by short arcs with the length of 3.2 km. In the middle straight sections A and G the FCC-ee collider foresees interaction regions for the two experiments. The additional experimental caverns in points F and H will only be used for the hadron collider. In the current version of the FCC-ee collider lattice the interaction point has a horizontal offset of 9.4 m to the FCC hadron machine to minimise synchrotron radiation created by the incoming beam and provide a non-zero dispersion function required for the local chromaticity correction section (see Figure 2). The layout of the booster therefore foresees its bypasses around the experiments on the inside following the footprint of FCC-hh. The two extended straight sections at points D and J have a length of 2.8 km and are foreseen for the installation of RF cavities in the case of FCC-ee.

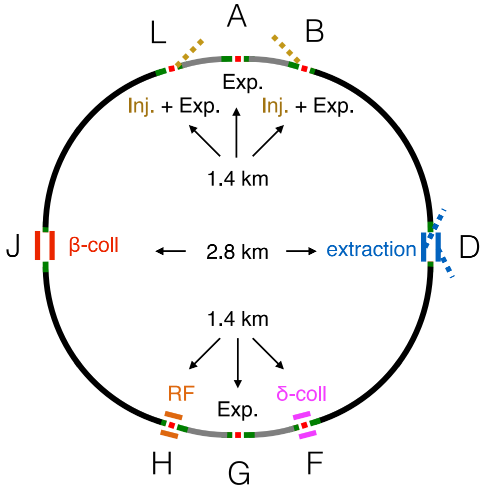

Figure 1: Layout the FCC hadron collider, which defines the geometry of the FCC main tunnel.

For the top-up injection the same beam emittances are aimed as in the FCC collider rings. The basic cell presented in Figure 3 is consequently similar to the collider's. A FODO design with a length of 50 m and phase advances of 90° in the horizontal plane and 60° in the vertical plane was chosen. In the arc sections sextupole magnets for chromaticity correction are installed at each side of every quadrupole. A maximum number of sextupoles is favoured in order to minimise their strengths and maximise dynamic aperture. Four 10-metre long dipole magnets per cell provide a dipole filling factor of 80 %. In the straight sections D and J they are replaced by RF cavities. In the other straight sections

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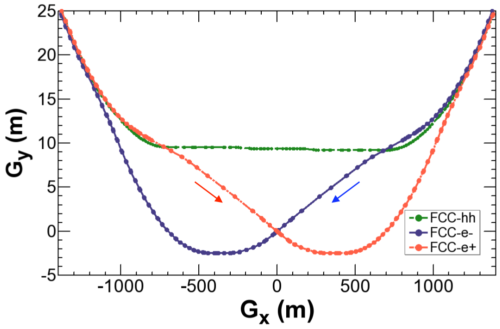

Figure 2: Geometry of the FCC-ee collider rings in the straight sections with the experiments [5]. The bypasses of the FCC-ee Booster will follow the footprint of FCC-hh.

the free space can be used for example for the injection and extraction schemes.

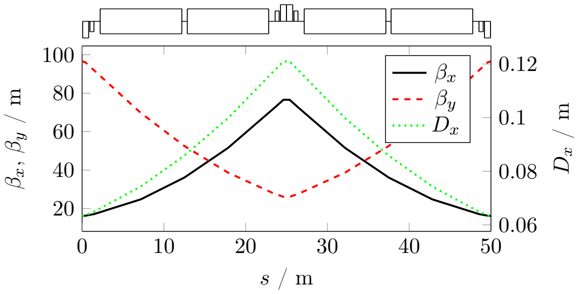

Figure 3: Beta functions and horizontal dispersion function of one FODO cell used in the arc sections of the FCC-ee Top-Up Booster Synchrotron. The phase advances are 90° in the horizontal plane and 60° in the vertical plane.

At the beginning and at the end of each arc section two half-bend cells are used to suppress dispersion. In addition, the first and last six quadrupoles of the straight sections are individually powered and used to provide a smooth transition of the lattice functions from the arcs to the straight sections as presented in Figure 4.

CHROMATICITY CORRECTION AND FIRST DYNAMIC APERTURE STUDY

The FODO cell phase advance in the extended straight sections D and J is used to set the tunes. In this first lattice the tunes $Q_x = 487.28$ and $Q_y = 327.34$ were chosen as a starting point. The natural chromaticity is $\xi_x = -542.4$ and $\xi_y = -450.7$ and was corrected to zero using one sextupole family per plane. An optimised positive value will be determined by tracking calculations in a later stage of the study. The momentum acceptance obtained by an energy scan is $\Delta p/p \approx \pm 4$ ‰. First tracking studies for 175 GeV beam energy without machine imperfections were conducted for 512 turns, which corresponds to 20 damping times. The dynamic aperture was determined by the survival of the particles after the tracking. With equilibrium emittances of $\epsilon_x = 0.92$ nm rad and $\epsilon_y = 2.5$ pm rad the dynamic aperture is $10\,\sigma$ in the horizontal plane and about $200\,\sigma$ in the vertical plane as shown in Figures 5 and 6. The color code represents the tunes of the surviving particles, which was calculated with a Fast Fourier Transformation. The dynamic aperture in the horizontal plane seems to be limited by the vertical tuneshift with amplitude. For short storage the stable range seems to be sufficiently large. Still, an optimisation of the working point is ongoing, and a more sophisticated sextupole scheme is being developed to suppress non-linear effects and increase the dynamic aperture. This first tracking did not involve the effects of synchrotron radiation and rf cavities. Further studies are under way.

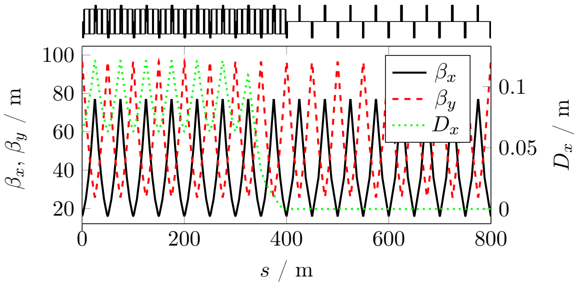

Figure 4: Transition of beta functions and horizontal dispersion function from the arc optics to the straight section optics.

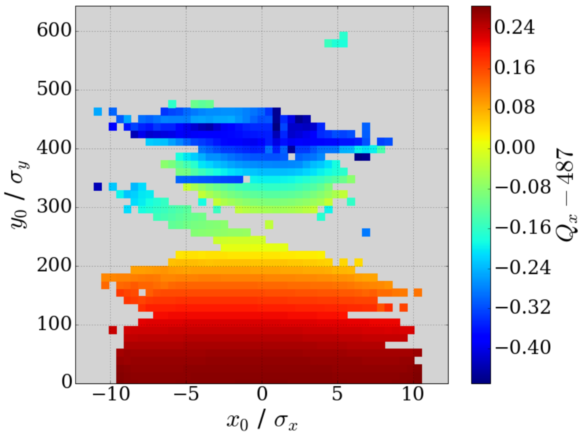

Figure 5: Dynamic aperture as a result of first tracking calculations. The colour bar indicates the horizontal tune of the particles. The nominal value is $Q_x = 487.28$.

CHALLENGES FOR THE FCC-ee BOOSTER DESIGN

While the main challenge for the injector chain is the production of the high currents up to 1.45 A for operation at the Z threshold at 45.6 GeV [3], the booster must provide stable beam dynamics for a large range of beam energies in a range from 6 GeV to 175 GeV, an energy gain by a factor of 30, which is large compared to operating synchrotrons. Table 1 presents the magnetic field of the bending magnets, equilibrium beam emittance and damping time for both discussed injection energies and lowest and highest operation energies of the collider. The very small injection energy of 6 GeV in combination with the very large bending radius of approx-

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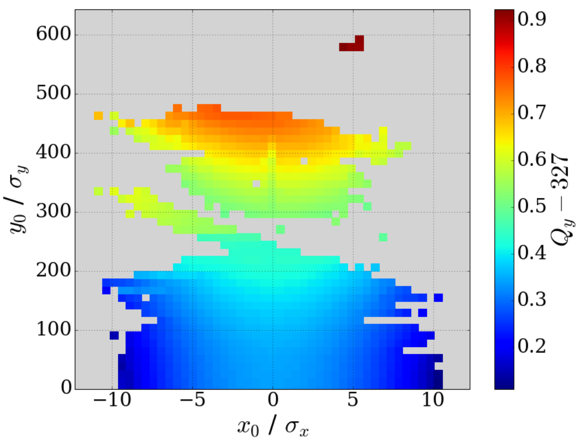

Figure 6: Dynamic aperture as a result of first tracking calculations. The colour bar indicates the vertical tune of the particles. The nominal value is $Q_y = 327.34$.

imately 10.5 km results in magnetic fields in the bending magnets of 19 Gs. From a technical design point of view this value seems difficult because of hysteresis effects and external perturbations. A higher injection energy to 20 GeV as provided by the pre-booster synchrotron would require larger magnetic fields of $B = 63$ Gs, which is considered to be more realistic.

The small injection energy also results in an ultra-small equilibrium emittance of $\epsilon_x = 0.001$ nm rad. The expected equilibrium for 20 GeV beam energy is 0.012 nm rad. At such small emittances collective effects like intra-beam-scattering but also single-bunch instabilities need to be investigated carefully and might limit the allowed beam intensity. However, the design emittance at the exit of the linac is 0.7 nm rad and at the exit of the pre-booster synchrotron 1.0 nm rad. As it can be seen in Table 1, the damping times $\tau = 9.94$ s and 368 s are for both injection energies much longer than the cycling time of the booster of about 12 s [2]. This means in normal operation the equilibrium beam parameters will not be reached and evolution of the beam emittance and its impact on the excitement of instabilities during the acceleration process must be investigated carefully.

At maximum beam energy of 175 GeV, the same amount of synchrotron radiation power of 50 MW is created as in one of the main collider rings. Therefore, the same absorber design is required to protect the machine components from radiation damage and heat load. In addition, the critical energy reaches 1 MeV, which in combination with the small vertical opening angle of a few µrad is very penetrating and puts demanding requirements on radiation protection [2].

The energy loss per turn reaches up to 7.9 GeV, which is 4.5 % of the total beam energy. As only two rf sections are foreseen, the lattice elements have to be optimised in their strength following the actual beam energy to avoid perturbing effects on the optics. This so-called tapering effect has already been proposed in the present FCC-ee lattice where each and every magnet will have to be adjusted individually [5, 6].

Table 1: Bending fields B, equilibrium beam emittance ϵ_x in the horizontal plane and damping times τ for both proposed injection energies and two extraction energies calculated with MAD-X.

E (GeV)	B (Gs)	ϵ_x (nm rad)	τ (s)
6.0	19	0.001	368
20.0	63	0.012	9.94
45.5	145	0.194	0.84
175.0	556	0.959	0.02

The injection scheme from the top-up booster to the main rings is still under investigation and might put additional constraints on the optics design of the booster [7].

CONCLUSION

A first lattice for the FCC-ee Top-Up Booster Synchrotron was set up following the footprint of the main collider including bypasses around the experiments. A FODO cell layout similar to the ones in the collider storage rings was chosen in order to obtain the same beam parameters. First tracking studies indicate sufficient dynamic aperture for stable beam storage. Very small bending fields and potential single-bunch instabilities suggest to include a pre-booster synchrotron to increase the injection energy from 6 GeV to 20 GeV. Next steps in the design process will focus on the evolution of the beam emittance during the acceleration process and the investigation of instabilities at low energies.

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