PROCEEDINGS OF SCIENCE

PoS(ICHEP2022)042

Status of the High Energy Booster of the lepton option of the future circular collider

B. Dalena,[a,*] **A. Chance,**[a] **F. Antoniou,**[b] **O. Etisken,**[c] **A. Mashal,**[d] **T. Raubenheimer,**[e] **M. Zampetakis**[b] **and F. Zimmermann**[b]

[a] *CEA Paris-Saclay and Paris Saclay University,*
F-91191 Gif-sur-Yvette, France
[b] *CERN,*
Esplanade des Particules 1, 1211 Geneva 23, Switzerland
[c] *Kirikkale University, Kırıkkale, Turkey*
[d] *Institute for Research in Fundamental Sciences, Iran*
[e] *Stanford National Accelerator Center (SLAC),*
Menlo Park, CA, USA

E-mail: barbara.dalena@cea.fr, antoine.chance@cea.fr

In the context of the FCC IS European study, which investigates the feasibility of a 100 km circular e^+e^- collider for the future high-energy physics research, we present the design status of the High Energy Booster (HEB) ring. In order to perform precision measurements of the Z, W and H bosons, as well as of the top quark, unprecedented luminosities are required. To reach this goal and to fill the collider, it is mandatory to continuously top-up inject some beam with emittances comparable to those in the collider, so as to maintain an intensity difference between colliding electron and positron bunches below a few %. The main challenges of the HEB design are achieving the collider equilibrium emittances with a fast cycle, and determining the minimum booster injection energy allowing for stable operation. We present the status of the optics design of the HEB, taking into account the above challenges, and the impact of magnetic field imperfections on the dynamic aperture at injection.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

---

[*] Speaker

1. Introduction

The HEB (High-Energy Booster) main aim is to accelerate the particles from about 20 GeV to the collision energy for the four different modes (Z, W, H, or ttbar). One FCC design criterion is that the two collider must be filled from zero in less than 20 minutes. In addition, continuous injection of a fraction of the beam (top-up injection) is mandatory, due to the short beam lifetime in the collider, caused by radiative Bhabha scattering and beamstrahlung, already in the case of two experiments. The lifetime is even shorter in the case of four experiments. One of the issues is that the collision energy (and thus the final energy in the booster) depends on the physics case [1]. The optimum optics for a particular case may be different from another. The cycle time of the Booster and the possibility to reach the collider emittances needs careful consideration. At the Z mode, the possibility to damp the vertical emittance, in order to reach the collider emittances, strongly depends on the beam emittance at injection in the booster ring, the ramp time, and the ramp structure. Another challenge is the injection energy. At injection, the magnetic field is so low in the dipoles that the field quality may hardly be reproducible from one cycle to another. The injection energy choice will have a strong impact on the preceding injectors' complex [2].
The HEB will be located in the same tunnel as the collider rings. In the FCC-ee CDR [3] the booster was placed with a horizontal offset of 1 m outside of the collider in the arcs. With the new fully symmetric layout, determined by a further site optimization, the booster could alternatively be installed on top of the collider in the arcs, to possibly ease the installation and maintenance work, and minimize tunnel dimensions. It is also proposed to move the hadron collider interaction point on top of the lepton interaction point, to minimize the tunnel size. The HEB has to bypass the experiments in these regions. Different options are under study for bypassing the experiments, also considering the synchrotron radiation photons coming from the booster that might hit the detectors, and effects of the detector stray field.

2. Optics options

In order to operate in top-up injection mode the beam emittance extracted from the booster should not be larger than those of the collider. Since the horizontal equilibrium emittance is determined by the lattice parameters, the same FODO cell structure as for the collider is considered. This also simplifies installation. The baseline optics is based on FODO cells with a length of about 52 m. We use different phase advances 60° for the Z and W mode operation, and 90° for the H and ttbar mode operation, as reported in [1]. The long straight sections are used to change the overall tune of the lattice. Current specifications for the magnetic elements of the W mode and ttbar mode operation are reported in Table 1. The arc FODO cell optics are shown in Fig. 1. The dipole magnetic length is fixed to be of 11.1 m. Space for interconnections and flanges between the dipoles, and the dipole and the other elements is considered. The main challenge is the low dipole field at the injection energy (20 GeV or below). A preliminary design for the main dipoles of the HEB ring has been presented in [4]. The dispersion suppressor is composed of 10 FODO cells of the same type of the arcs. The straight insertions optics are simple FODO cells with zero dispersion. The cell length of each insertion can be chosen individually, because it has no impact on the emittances. In the case of the extended straight insertions (namely B, F, H, and L) the cell

Table 1: Magnetic elements specifications for W and ttbar modes.

Magnet	**Parameter**	**Unit**	Value 60°	Value 90°
Dipole	Field at injection (20 GeV)	G	71	71
	Field at W/ttbar energy (80/182.5 GeV)	G	284	650
	Length	m	11.1	
Quadrupole	Gradient at injection (20 GeV)	T/m	1.74	2.5
	Gradient at W/ttbar energy (80/182.5 GeV)	T/m	6.9	22.5
	Length	m	1.5	
Sextupole	Gradient at injection (20 GeV)	T/m^2	75	174
	Gradient at W/ttbar energy (80/182.5 GeV)	T/m^2	300	1582
	Length	m	0.5	

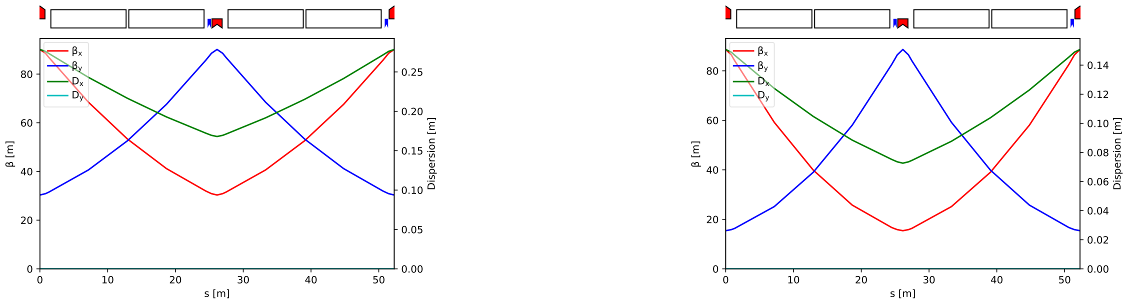

Figure 1: Arc FODO cells for the Z and W modes (left) and for the H and ttbar modes (right).

length is 104 m, in order to accommodate the RF cavities in the cryo-modules [5]. Currently, RF cavities are installed in the extended insertions H and L, but all the RF system of the Booster could be installed in the one insertion, e.g. H or also F, to further optimize the cost of the infrastructure. Two types of RF system are foreseen for both the collider and the HEB, namely 400 MHz and 800 MHz; the latter will exclusively be used for the operation mode at maximum beam energy. The 400 MHz RF system consists of 4 cells of 0.375 m each, while the 800 MHz system is made of 5 cells with a cell length of 0.1875 m. The total cryo-module lengths are 11.4 m and 7.5 m, for the 400 MHz and the 800 MHz RF system respectively. In one scenario, a total number of 3, 13, 34, 34 cryo-modules of the 400 MHz RF system may be installed in the insertion L, for the Z, W, H and ttbar operation modes, respectively. The 120 cryo-modules of the 800 MHz RF system are installed in the insertion H, for the ttbar operation mode only. In order to further reduce the cost of this system, the RF group has proposed to use the 800 MHz RF system only, for all the operation modes of the HEB ring [6]. The injection and extraction are foreseen in the insertion B, for which optics and main elements are under study [7].

3. Booster cycle time and emittances

The short collider lifetime (order of minutes) implies a ramp time of the order of one second for the four operation modes. The transverse damping time for an injection energy of 20 GeV is about 9 s. Therefore, depending on the injected beam parameters, on the extraction energy and on the energy ramp function, there is the possibility that the collider emittances could not be reached. This is the case for the last bunch injected into the booster before ramping the energy for the Z operation mode, as shown in Fig. 2. This can also be the case of earlier injected bunches whose emittance increases due to Intra-Beam scattering (which starts to be relevant after 10 s) during the accumulation of the bunches into the HEB. This case is illustrated in Fig. 3, considering the LINAC beam parameters of Ref. [8] and a linear energy ramp. To address this issue, several options are considered: adding a damping wiggler to increase the synchrotron radiation integral I_2, which consequently reduces the damping time at 20 GeV [1]; adding 2 seconds at the extraction energy. A third possibility would be to use two dipole families to increase both the I_2 integral and the dipole magnetic field at injection. The additional family has a reverse field at injection, allowing for an increase the I_2 synchrotron integral and to double the magnetic field of the other family. At extraction, all the families have the same polarity in order not to increase the power consumption.

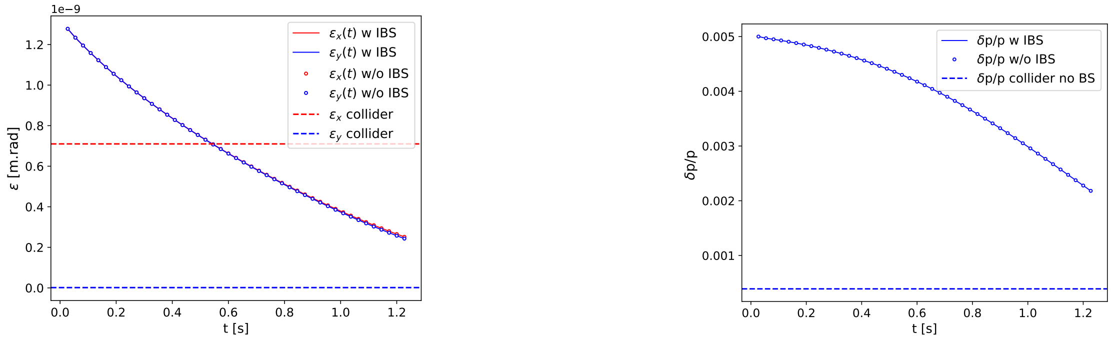

Figure 2: Evolution of transverse emittances (left) and energy spread (right) during a linear energy ramp of ~ 1 s. The injected beam normalized emittance are 50 µm. The injected beam energy spread and bunch length are 0.1 % and 1 mm, respectively.

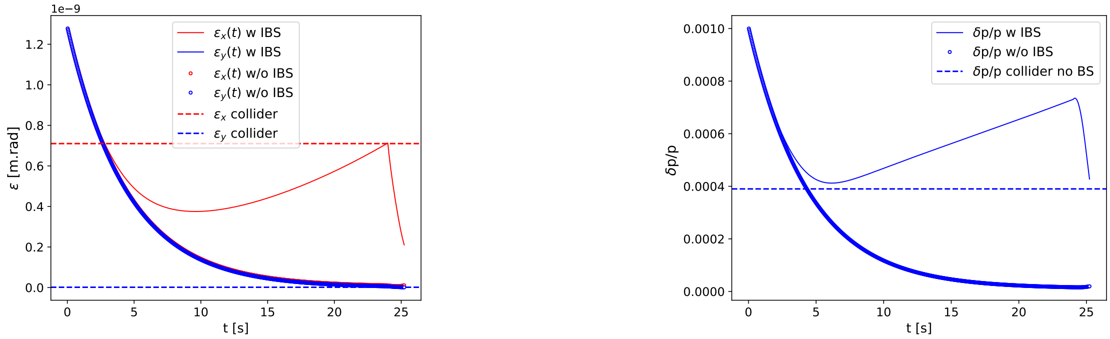

Figure 3: Evolution of transverse emittances and energy spread during the bunch accumulation into the Booster (24 s) and a linear energy ramp of 1 s. The injected beam normalized emittance is taken to be 50 µm. The injected beam energy spread and bunch length are 0.1 % and 1 mm, respectively.

4. Acceptance at injection

In section 3 we discussed how the cycle time and the damping rates impose limitations on the beam parameters at injection into the HEB. The Dynamic Aperture (DA) at injection will also limit the allowed beam emittances coming from the pre-injectors. A DA of about 15 beam sizes in the transverse plane, and a Momentum Acceptance about ±5 times the energy spread are the target for safe injection into the HEB. Particles with initial transverse amplitude up to 25 mm and energy spread between -2% and +2% are tracked for 4500 turns (i.e. $\sim$ 15% of the damping time at 20 GeV). The DA is defined as the initial particle amplitude that stays stable over 4500 turns. Figure 4 shows the horizontal DA in millimetres, for the 60° and the 90° phase advance optics.

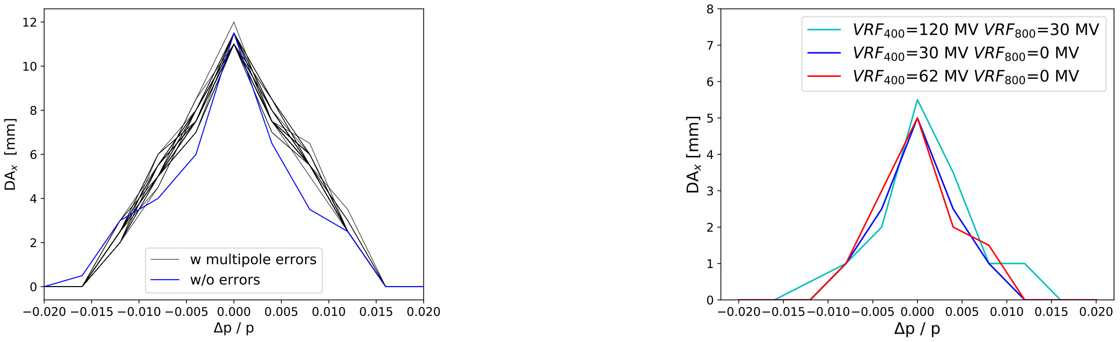

Figure 4: Horizontal dynamics aperture for an injection energy of 20 GeV, for the 60°(left) and 90°(right) phase advance optics with and without high orders dipole field errors.

Without high order field errors of the main dipoles, the horizontal DA of the 90° optics is greatly reduced due to large sextupole strengths, with a slight dependence on the RF voltage. The strong sextupoles, required for the chromaticity correction, excite synchro-betatron resonances. Considering the transverse β functions values and a transverse normalized emittance of 50 µm (assumed output of the main LINAC), the available DA is above the target of 15σ (beam sizes) for the 60° phase advance optics, but below this target for the 90° optics. Ways to improve the 6-D DA are under investigation. For the similar Chinese version of the future lepton collider (called CEPC) prototypes for the main dipole of the HEB were already built. The measured field quality for the Cosine-Theta (CT) design is reported in Table 2. Using these values, as systematic part and taking

Table 2: Measured field quality at injection for the CepC main dipole prototypes at a radius of 26 mm. CT stands for Cosine-Theta design B1 is the main dipole field of 56 G (at 20 GeV). (Courtesy of Jie Gao)

Relative field Harmonics	**CT dipole [10^{-4} unit]**
B3/B1	5.41
B4/B1	1.05
B5/B1	−3.66
B6/B1	−2.38
B7/B1	2.16

PoS(ICHEP2022)042

$\pm 3 \times 10\%$ of them as random component of the magnetic field errors, the horizontal DA for the 60° is not much reduced (as shown in Fig. 4(a)).

5. Conclusion

We are investigating different options for the design of the HEB of the future circular electron-positron collider. The layout of the HEB has been updated following the one of the collider, except in the insertion regions. Realistic optics for the four different modes of operation have been generated, taking into account also space for flanges and interconnections, and the RF systems. First studies concerning operation and stability show that further optimization of the HEB cycle time, RF parameters and optics are required, in particular, to reach the target transverse emittances and energy spread at extraction of the HEB for the Z operation mode. Moreover, the possibility to increase the 6-D Dynamic Aperture and Momentum Aperture for the H and $t\bar{t}$ operation modes is under investigation. In the near future, the design of the injection and extraction insertion, and of the arcs orbit corrector scheme will be included.

Acknowledgements

This work was supported by the European Union's Horizon 2020 Research and Innovation programme under grant no. 951754 (FCCIS).

References

[1] B. Haerer and T. Tydecks, *Lattice Design and Dynamic Aperture Studies for the FCC-ee Top-Up Booster Synchrotron. arXiv:2111.14462* (2021). `https://arxiv.org/abs/2111.14462`

[2] P. Craievich et al., *The FCCee Pre-injector complex.* `https://accelconf.web.cern.ch/ipac2022/papers/wepopt063.pdf`

[3] A. Abada, M. Abbrescia, S.S. AbdusSalam et al., *FCC-ee: The Lepton Collider. Eur. Phys. J. Spec. Top.* 228, 261–623 (2019). `https://doi.org/10.1140/epjst/e2019-900045-4`

[4] J. Bauche, *Status of Collider and Booster Magnets for FCC-ee* presented at *FCC week 2021* `https://indico.cern.ch/event/1064327/contributions/4888487`

[5] F. Valchkova-Georgieva, *Integration of FCC-ee RF Sections* presented at *FCC week 2021* `https://indico.cern.ch/event/1064327/contributions/4888567/`

[6] F. Peauger, *Baseline & Cavity options for FCC-ee* presented at *FCC week 2021* `https://indico.cern.ch/event/1064327/contributions/4888581/`

[7] E. Howling, *Design Studies Towards the FCC-ee Booster Ring Injection and Extraction, CERN-STUDENTS-Note-2022-146* `https://cds.cern.ch/record/2826991`

[8] S. Bettoni, *FCC-ee Linacs design from 200 MeV up to 6 GeV beam energy* presented at *FCC week 2021* `https://indico.cern.ch/event/1064327/contributions/4883218/`