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STATUS AND PLANS FOR THE HIGH ENERGY BOOSTER OF THE FUTURE ELECTRON-POSITRON COLLIDER FCC-EE*

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Abstract

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 status of the High Energy Booster (HEB) ring. The HEB will be located in the same tunnel as the collider and should have the same circumference. The main difference is to have a bypass near the experiments to avoid perturbing the detectors. 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 beams with a comparable emittance and bunch length to the collider ones. One challenge of the HEB is in the fast cycling time allowing to reach the collider equilibrium emittance, especially for the Z mode. We present the status of the layout and optics design of the HEB taking into account these challenges. A special focus will be made on the cycling considerations.

INTRODUCTION

The main purpose of the HEB (High-Energy Booster) is to accelerate the particles from about 20 GeV to the collision energy for the four different modes (Z, W, H, or $t\bar{t}$). Radiative Bhabha scattering and beamstrahlung imply a short beam lifetime in the collider. The lifetime is even shorter in the case of four experiments. One booster design objective is to fill the $e^+ - e^-$ collider from zero in less than 20 minutes and also to continuously inject a fraction of the beam (top-up injection). The cycle time of the HEB and the possibility to reach the collider emittances need careful consideration. Indeed, the injection energy choice will have a strong impact on the preceding injectors' complex [1]. At the Z mode, the cycling optimization strongly depends on the beam emittance at injection in the booster ring, the ramp time, and the ramp structure in order to reach the collider emittances. The HEB will be located in the same tunnel as the collider rings. Since the FCC-ee CDR [2], the layout baseline is the HEB on top of the collider in the arcs, with a possible horizontal and longitudinal offset. The main motivation is to ease the installation and maintenance work, and minimize tunnel dimensions. The HEB bypasses the experiments in the four shorter straight insertions with a transverse offset of 8 m to 10 m.

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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 Ref. [3]. The main reason of a smaller phase advance at Z/W operation mode is to handle the microwave instabilities due to a greater current thanks to a twice larger momentum compaction. More investigation on the collective effects at injection are ongoing to check if a Copper coating is not sufficient to handle this issue. The long straight sections are used to change the overall tune of the lattice. Minimum and maximum current specifications for the magnetic elements are reported in Table 1. Space for interconnections and flanges between the dipoles, and the dipole and the other elements is considered. A preliminary design for the main dipoles of the HEB ring has been presented in Ref. [4]. The arc FODO cell optics are shown in Fig. 1.

Table 1: Magnetic Element Specifications

Magnet	Field	Unit	Value
Dipole	Min/Max	G	71/650
	Length	m	11.1
Quadrupole	Min/Max	T/m	1.74/22.5
	Length	m	1.5
Sextupole	Min/Max	T/m^2	75/1582
	Length	m	0.5

The dispersion suppressor is made of 10 FODO cells of the same type as the arcs. To enlarge the dynamic aperture, the sextupole scheme is based on a non-interleaved scheme with a phase advance of 180° between two sextupoles of a pair. First tolerances of magnets imperfections and corrector strength for the orbit control of the baseline optics are reportes in Ref. [5].

ALTERNATIVE OPTICS

Maintaining the possibility to have 60°/90° implies to have a different cabling for the different operation modes. Moreover, the number of sextupoles is roughly doubled. We propose an alternative scheme which enables to tune the momentum compaction by keeping the same non-interleaved

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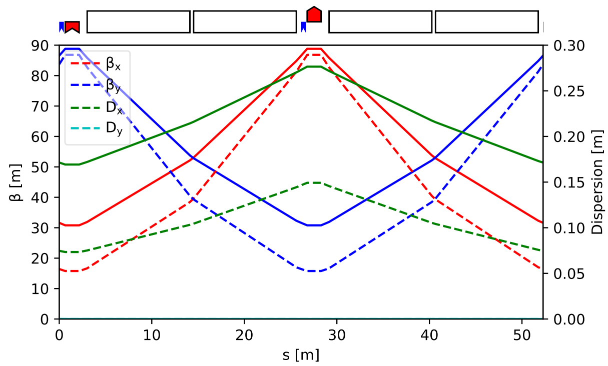

Figure 1: Arc FODO cells for the Z and W modes (solid line) and for the H and ttbar modes (dashed line).

scheme for all operation modes. The principle is to create a dispersion and betatron wave at one quadrupole near a sextupole. We assume for instance that the integrated quadrupole strength is modified by Δk; the quadrupole near the other paired sextupole is modified by $-\Delta k$ (see Fig. 2). The phase advance between the two quadrupole centres is 180° in both planes. This way, the betatron wave is cancelled in the second quadrupole contrary to the dispersion wave (because the betatron wave frequency is twice the dispersion one). The other advantage is also not to change the tune of the cell. With thin lens approximation, applying a strength of $\Delta k \approx \frac{\sqrt{x}}{2\sqrt{3}}$ gives a relative change of x on the momentum compaction.

The advantages of this scheme are to simplify the cabling and sextupole distribution; to enable the momentum compaction tuning during the ramp and thus to get a smaller equilibrium emittance for the Z/W modes; to allow any arc pattern if the phase advance between the sextupoles is still 180°. The drawbacks are an additional power supply for the quadrupoles (but that should be less expensive than increasing the number of sextupoles if we have to keep non-interleaved scheme for 60°/90° cells), a larger equilibrium emittance than a FODO cell giving the same momentum compaction, and a possible reduction of the dynamic aperture and momentum acceptance.

RF PARAMETERS AND FREQUENCY CHOICE

In the case of the extended straight insertions (namely B, F, H, and L) the cell length is 104 m, in order to accommodate the RF cavities in the cryo-modules [6]. Currently, RF cavities are installed in the extended insertions H and L, but all the RF system of the Booster could be installed in one insertion, e.g. H or also F, to further optimize the cost of the infrastructure. One driver of the RF total voltage budget is the bunch length needed at extraction for different energy modes. Recently, the base design of the RF frequency has changed from 400 MHz to 800 MHz, requiring a revision of the total voltage budget. Assuming no energy gain

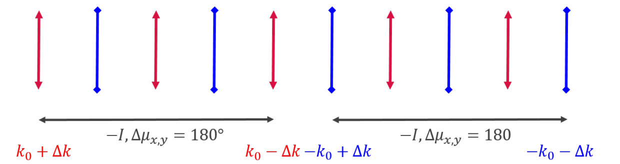

Figure 2: Sheme to tune the momentum compaction. The focusing/defocusing quadrupoles are respectively in red/blue.

($E_{\text{gain}} = 0$) at injection and extraction, one can calculate the resulting RF voltage using the Eq (1):

$$V_{RF} = \sqrt{\left(\frac{C^2\sigma_e^2 E_t \eta}{2\pi\nu_{RF}\sigma_z^2\beta^3}\right)^2 + \left(E_{\text{gain}} + U_0\right)^2} \qquad (1)$$

In this equation, C is the booster circumference, σ_z the bunch length, E_t the total energy, $\eta \simeq -\alpha_c$ the slippage factor, β the normalized velocity, ν_{RF} the RF cavities frequency, U_0 the synchrotron energy loss per turn, and σ_e the energy spread.

At injection energy, the momentum acceptance is taken as a criterion for the calculation of the cavities RF voltage budget by solving Eq. (2):

$$\delta_p = \frac{2Q_s(V_{RF})c}{C\nu_{RF}\alpha_c}\sqrt{\tan\phi_s(V_{RF})\left(1 + \phi_s(V_{RF}) - \frac{\pi}{2}\right)} \quad (2)$$

with $Q_s(V_{RF})$ the synchronous tune and $\phi_s(V_{RF})$ the synchronous phase.

Table 2 shows that the frequency change from 400 MHz to 800 MHz allows a smaller total RF budget at extraction. However, taking the momentum acceptance as a requirement at injection almost doubles it.

Table 2: Total RF voltage budget for the different energy modes of the FCC-ee HEB for two RF cavities frequencies.

Modes	Z	W	H	$t\bar{t}$	Units
Energy	45.6	80	120	182.5	GeV
α_c	14.9		7.34		10^{-6}
			Injection at 20 GeV		
σ_z			4		mm
δ_p			3		%
$V_{RF,400}$	53.6		27.6		MV
$V_{RF,800}$	104.8		52.8		MV
			Extraction		
σ_z	4.38	3.55	3.34	1.94	mm
δ_p	4.38	3.55	3.34	1.94	%
$V_{RF,400}$	124.6	1023.2	2185.6	14205.4	MV
$V_{RF,800}$	83.9	623.6	2038.3	11554.9	MV

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

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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. 3. This

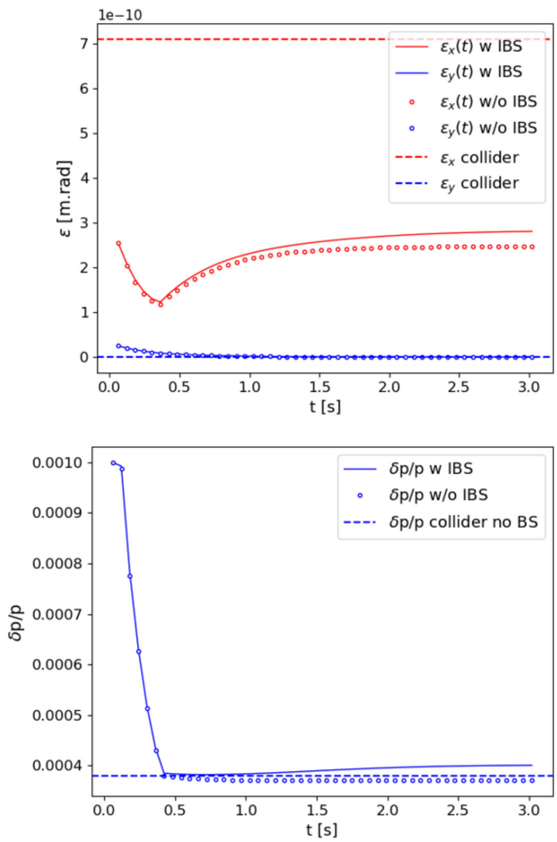

Figure 3: Transverse emittances and energy spread during a linear energy ramp of ~ 1 s. The injected beam normalized emittance are 10 µm. The injected beam energy spread and bunch length are 0.1 % and 1 mm, respectively.

can also be the case of earlier injected bunches whose emittance increases due to Intra-Beam scattering and wakefields (which becomes relevant after 10 s) during the accumulation of the bunches into the HEB. This case is illustrated in Fig. 4, considering the LINAC beam parameters of Ref. [8] and a linear energy ramp. The current baseline to address this issue is to add a flat-top (as reported in Table 3) at extraction energy to damp the beam and reach the target emittances and energy spread. The impact is to increase the filling time of the collider.

CONCLUSION

We have presented the current optics of the booster, based on FODO cells. An alternative optics is under study to be able to tune the momentum compaction during the acceleration. The RF budget has been updated to take into account

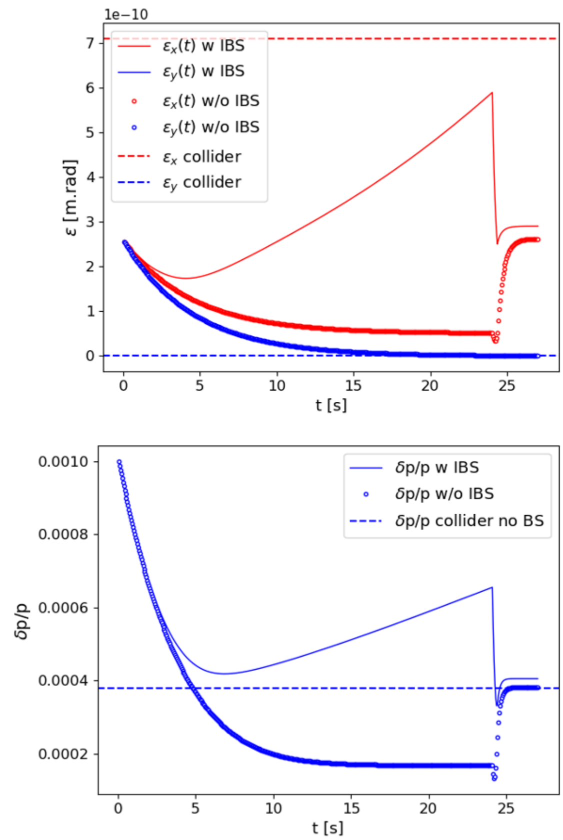

Figure 4: Transverse emittances and energy spread during the bunch accumulation into the Booster (24 s) and a linear energy ramp of 1 s. The injected beam normalized emittance is taken to be 10 µm. The injected beam energy spread and bunch length are 0.1 % and 1 mm, respectively.

Table 3: High Energy Booster emittances reach and flat top additional time for the Z operation mode, according to 3 different set of injected beam parameters.

Parameter	Unit	Value		
$\epsilon_{x_{in}}$ (norm)	µm	50	10	10
$\epsilon_{y_{in}}$ (norm)	pm	50	10	1
$\delta_{p_{in}}$	%		0.1-0.15	
$\epsilon_{x_{ex}}$ (geo)	µm		<0.3	
$\epsilon_{y_{ex}}$ (geo)	pm		<1.42	
$\delta_{p_{ex}}$	%		0.04	
flat top time	s	~2.6	~1.9	~1.0

the possibility to use 800 MHz cavities for all modes. Finally, the cycling of the booster has been presented. The IBS is not negligible during the accumulation and should be taken into account. The target emittances and energy spread can be reached with the cost of a flat top at extraction energy. The next steps are to perform tracking studies to validate the whole acceleration by integrating collective effects and IBS.

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