DESIGN GUIDELINES FOR THE INJECTOR COMPLEX OF THE FCC-ee[*]

Y. Papaphilippou, F. Zimmermann, CERN, Geneva, Switzerland,
K. Oide, KEK, Ibaraki, Japan, M. Aiba, PSI, Villigen, Switzerland,
L. Rinolfi, JUAS-ESI, Archamps, France and D. Shwartz, BINP, Novosibirsk, RAS

Abstract

The design of the injector of the FCC-ee, a high-luminosity e+/e- circular collider of 100 km in the Geneva area, is driven by the required particle flux for ring filling or top-up and for a variety of energies, from 45.6 to 175 GeV. In this paper, a set of parameters of the injector complex is presented, fulfilling the collider needs for all running scenarios. In particular, the challenges of the booster ring design are detailed, focusing on issues of optics, layout, low bending fields, injection schemes to the collider for maximizing transfer efficiency and synchrotron radiation handling.

REQUIREMENTS FOR THE FCC-ee INJECTOR COMPLEX

The injector complex of the FCC-ee, a high luminosity e+/e- collider with a beam energy of 45.6 to 175 GeV and a circumference of 100 km [1], is comprised by an e+/e- LINAC (up to around 10 GeV), a Pre-Booster Damping Ring (PBDR) from around 10 to 20 GeV and a full energy Booster Ring (BR), integrated in the same tunnel as the collider. An extra optional ring with wigglers for rapid radiative polarisation (at an energy 1-2 GeV) [2] is being also considered. A basic schematic layout of the injector complex can be found in Fig. 1.

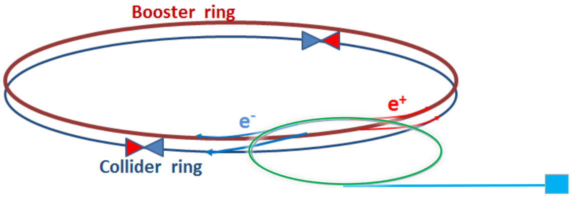

Figure 1: Schematic layout of the FCC-ee injector complex.

The short lifetimes from radiative Bhabha scattering and Brehmsstrahlung, which can drop down to a few minutes, depending on the collider parameter sets and different energy flavours, require continuous top-up injection from the BR. A set of parameters that define the required particle flux coming from the BR is presented in Table 1. For defining the injector cycle and flux, it is assumed that a 2 % current decay occurs between top-ups. The top energy of FCC-ee defines the minimum time between injections for each species and is equal to 69 sec for this parameter set, although it can be significantly shorter. Considering a maximum 50 % duty factor due to the interleaved e+/e- injection, and a minimum lifetime of around 10 min, the injections should be made every 12 sec, at a rate of around 0.1 Hz. The full collider filling, though, imposes a more stringent constraint. Assuming 20 min of filling time and 80 % of transfer efficiency along the injector chain, the main flux challenge occurs for the full filling of the FCC-eeZ and is equal to 3.1×10^{12} p/sec. Although this flux is not far away from the positron production rate of SuperKEKB (2.5×10^{12} p/sec), this may still be a challenge, due to the large amount of bunches necessary to fill FCC-ee. A positron production scheme fully compatible with FCC-ee is the one of CLIC with a positron flux of 1-2×10^{14} p/sec [3].

A maximum ramp rate can be also estimated considering a 10 sec cycle with linear ramp and short flat bottom and top of 100 ms. The fastest rate corresponding to the highest energy is equal to 32 GeV/sec, which is still two times lower than the one of the SPS at CERN (around 62 GeV/sec) and within the capabilities of modern magnet systems and power convertors.

POSSIBLE FCC-ee INJECTOR SCHEME

For reaching a high particle production rate, a version of the LINAC and positron production scheme of CLIC are used as a basis. Table 2 displays a list of parameters for the injection schemes for the different collider energies and filling modes (top-up or full filling). A 2 GHz RF system is used in the LINAC (running at a repetition rate of 50 Hz), although other more popular frequencies could be envisaged, such as 3 GHz [4]. Around 2×10^9 p/b is the maximum bunch population necessary (to be compared with 6×10^9 p/b captured in the pre-DR for CLIC), in trains of 80 to 6100 bunches (depending on the FCC-ee flavour). The maximum total charge of the LINAC pulse is around 3×10^{12} particles (480 nC), as compared to 2×10^{12} (320 nC) for CLIC.

In the current scheme, the LINAC pulses are injected 5 times in the SPS which serves as the PBDR, in a similar operational scenario as the one of LEP. The injection energy is at around 10 GeV or lower, e.g. it was 3.5 GeV for LEP. The LINAC bunch trains are injected in a 400 MHz bunch structure (as for the collider), so that in every SPS bucket fit 5 LINAC bunches. Indeed, a new 400 MHz RF system will be needed in the SPS with the required power (and voltage) for coping with the energy loss per turn at the top energy of around 20 GeV. In order to allow time for fixed target physics in parallel to the collider filling, the SPS duty factor is equal to 0.5 or lower, with a maximum of 5 e+/e- cycles of 1.2 s in a supercycle of maximum 12 s. The e+/e- trains are injected in an interleaved way into the BR, at a flat bottom with a maximum duration of 6 s (or lower) to be accelerated in 3 s to the required extraction energy of FCC-ee. The maximum

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Table 1: FCC-ee Requirements and BR Target Flux

Parameters [unit]	Z		WW	ZH	tt	LEP2
Energy [GeV]	45.6		80	120	175	104
Average Current [mA]	1450		152	30	7	1
No. of bunches	30180	91500	5260	780	81	4
Bunch Population [10^{11}]	1.0	0.33	0.6	0.8	1.7	4.2
Lifetime [min]	94	185	90	67	57	434
Time between injections [sec]	114	224	109	81	69	263
Injected top-up bunch population [10^{11}]	604.2		63.2	12.5	2.8	0.34
Particle flux for top-up [10^{11}p/sec]	6.6	3.4	0.7	0.19	0.05	0.001
Particle flux for full filling [10^{11}p/sec]	31.3		3.3	0.7	0.1	0.02
Booster ring ramp rate [GeV/sec]	5.2		12.2	20.4	31.6	

full filling time corresponds to 20 min for FCC-ee-Z and it reduces significantly for the other collider energies.

The parameters are tailored in a way that the top-up rate is compatible with all required lifetimes, down to 14.4 s for both species. An alternative scenario with a new “green-field" PBDR is been worked out [5], in order to increase the duty factor and thereby reduce the flux requirements.

BOOSTER RING DESIGN

The BR is installed in the same tunnel as the collider and naturally needs to have a similar geometry. A preliminary optics design was undertaken by cloning the “inner” quarter-ring of the collider and neglecting the IR. It is a two-fold symmetric lattice with a mirror symmetry. A schematic layout of half of the ring is presented in Fig. 2. The inner arc and the bypass for avoiding the experiments is chosen to be compatible with the layout of FCC-hh, as shown in Fig. 3, with a 9.4 m separation between the beam in the BR and the collider beam at the IP.

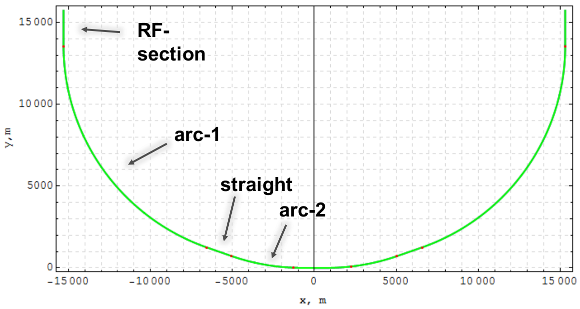

Figure 2: Basic geometry of half of the booster ring.

The optics of half of the ring and the bypass are presented in Fig. 4, all based on standard FODO cells. A set of BR parameters is shown in Table 3.

Due to the fact that the BR geometry is identical to the one of the collider, a low emittance at extraction is obtained quite naturally due to the small bending angle. This guarantees a good injection efficiency and eases the top-up procedure. On the other hand, if the same optics is kept throughout the cycle, ultra-low geometrical emittances are obtained at injection, down to 24 pm, which are unprecedented. Although the damping times at injection are relatively slow (around 11 s in the transverse plane), a detailed analysis of collective effects and in particular of Intrabeam Scattering will be necessary. Another option would be to detune the arc optics during the cycle, although, in that case, the straight section optics should follow, for keeping the BR tune relatively constant.

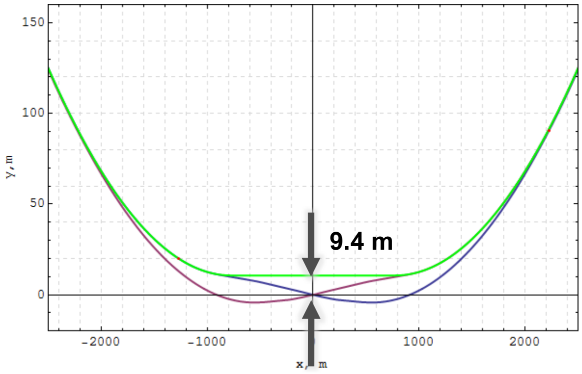

Figure 3: Geometry of the booster ring in the experimental by-pass area.

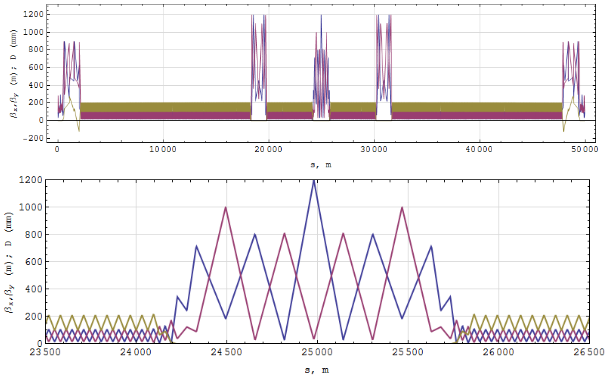

Figure 4: Optics functions for half of the BR ring (top) and the experimental by-pass (bottom).

The energy loss per turn is determined by the energy and ring geometry, thereby it is the same as the one of the col-

Table 2: FCC-ee Injector Parameters for a 2 GHz LINAC

Parameter [unit]	Z		WW		ZH		tt	
Energy [GeV]	45.6		80		120		175	
Type of filling	Full	Top-up	Full	Top-up	Full	Top-up	Full	Top-up
LINAC bunches	1830	6100	1315		780		80	
LINAC repetition rate [Hz]	50							
LINAC RF freq [MHz]	2000							
LINAC bunch population [10^9]	1.65	0.06	1.50	0.30	1.54	0.40	1.62	0.87
No. of LINAC injections	5							
SPS/BR bunch spacing [MHz]	400							
SPS bunches/injection	366	1220	263		156		16	
SPS bunch population [10^{10}]	0.83	0.03	0.75	0.15	0.77	0.20	0.81	0.44
SPS duty factor	0.5		0.44		0.17		0.17	
SPS / BR bunches	1830/9150	6100/30500	1315/5260		780/780		80/80	
SPS / BR cycle time [s]	1.2 / 12		1.2 / 10.8		1.2 / 7.2		1.2 / 7.2	
Number of BR cycles	50	9	10	1	13	1	27	1
Transfer efficiency	0.8							
Total number of collider bunches	91500		5260		780		80	
Filling time (both species) [sec]	1200	216	216	21.6	187.2	14.4	388.8	14.4
Injected bunch population [10^{10}]	3.3	0.07	6.0	0.12	8.0	0.16	17.4	0.35

Table 3: Booster Ring Parameters

Top Energy [GeV]	45.6	80	120	175
Cycle time [s]	12			
Circumference [m]	99918.2			
Bending radius [m]	11653.8			
Injection energy [GeV]	20			
Dipole length [m]	10.5			
Emittance @ inj. [nm]	0.024			
Emittance @ ext. [nm]	0.12	0.38	0.85	1.8
Bending field @ inj. [G]	57			
Bending field @ ext. [G]	129	229	343	509
Energy Loss / turn @ inj. [MeV]	1.21			
Energy Loss / turn @ ext. [MeV]	31.1	310	1572	7109
Trans. damp. time @ inj. [turns]	32974			
Trans. damp. time @ ext. [turns]	2895	516	153	50
Average current [mA]	36.3	19.0	2.9	0.31
Average power @ inj. [kW]	44.1	23.1	3.5	0.4
Average power @ ext. [MW]	1.19	5.9	4.5	2.2
Average power over 1 cycle [kW]	96	544	630	306
Power from dipoles @ ext. [W]	171	847	651	317
Bends' power dens. @ ext. [W/m]	16	81	62	30
Critical energy [MeV]	0.02	0.10	0.33	1.02
Radiation angle [μrad]	11.2	6.4	4.3	2.9

lider at extraction, with a maximum of 7.1 GeV at 175 GeV. Consequently, a similar RF system as the collider will be needed. On the other hand, the corresponding RF power is much lower, and the system could be pulsed through the cycle. Due to the fact that the bending field has to be kept low at extraction, as the energy loss/turn at flat top is already extremely high, the corresponding field at injection is quite low and equal to 57 Gauss. This may necessitate a compensation of eddy currents, hysteresis effects and an appropriate shielding from the FCC-ee main magnets.

The average current for full filling is relatively low, varying from a few to 36 mA. The maximum average power at injection is around 44 kW and raises up to 6 MW at extraction. A more significant figure is the power density at the bends, which exceeds by far the canonical 1 W/m limit, in all extraction energies and calls for shielding of the synchrotron radiation. What seems more of a challenge, though, is the critical energy, which, for the highest collider energy, reaches the same value of 1 MeV. With vertical radiation angles of a few μrad, this radiation will be extremely penetrating and can irradiate the tunnel air. A demanding shielding, absorption scheme and vacuum chamber design will be necessary to deal with these potential radiation risks.

SUMMARY

A preliminary design of the FCC-ee injector complex was undertaken, setting-up the different design guidelines and elaborating a parameter list based on simple scalings. There is indeed a series of future optimisation steps, including a detailed LINAC design and positron production scheme, probably based to an upgraded version of the CLIC injector. Regarding the BR, apart from a robust linear optics design and study of non-linear dynamics, collective effects should be studied with emphasis to Intrabeam scattering. An important aspect of the design is the BR integration to the tunnel, with all the different issues regarding shielding of both synchrotron radiation and magnetic fields. Another important design consideration is polarisation and the necessary insertions to achieve it. Finally, a preliminary design of the top-up injection schemes to the collider has been developed and will need to be adapted to the final BR and collider parameters [6].

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