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THE FCCee PRE-INJECTOR COMPLEX

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Abstract

The international FCC study group published in 2019 a Conceptual Design Report for an electron-positron collider with a centre-of-mass energy from 90 to 365 GeV with a beam currents of up to 1.4 A per beam. The high beam current of this collider create challenging requirements on the injection chain and all aspects of the linac need to be carefully reconsidered and revisited, including the injection time structure. The entire beam dynamics studies for the full linac, damping ring and transfer lines are major activities of the injector complex design. A key point is that any increase of positron production and capture efficiency reduces the cost and complexity of the driver linac, the heat and radiation load of the converter system, and increases the operational margin. In this paper we will give an overview of the status of the injector complex design and introduce the new layout that has been proposed by the study group working in the context of the CHART collaboration. In this framework, furthermore, we also present the preliminary studies of the FCC-ee positron source highlighting the main requirements and constraints.

INTRODUCTION

The FCC-ee injector complex must provide beam for top-up injection in the booster rings supporting a beam lifetime of about 18 minutes on Z pole and as low as 12 minutes at high energy. It must also allow for a filling from zero (alternating bootstrapping injection) within at most half an hour. For this purpose, the FCC-ee CDR [1] considers a 6 GeV linac, with at most 2 bunches per RF pulse, with a repetition rate up to 200 Hz. In this context, the FCC-ee Injector Study was created as a collaboration between PSI and CERN with some external partners, such as CNRS-IJCLab (Orsay), BINP (Novosibirsk), INFN-LNF (Frascati) and SuperKEKB (Tsukuba) as an observer. The project has two deliverables: the revision of the baseline FCC-ee injector design as published in the FCC-ee CDR [1] -including a cost estimate- and the proof of principle of the positron source through the PSI Positron Production (P^3 or P-cubed) experiment at PSI.

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Table 1: Target Parameters for the Two Main Scenarios

	Baseline	HE Linac
Ring for injection	PBR	BR
Injection energy [GeV]	6	20
Bunch population 10^{10} (nC)	3.47 (5.55)	3.12 (5.0)
Repetition rate [Hz]	200	200
Number of bunches	2	2
Bunch spacing [ns]	15, 17.5, 20	15, 17.5, 20
Rms norm. emit. [mmmrad]	50, 50	50, 50
Rms bunch length [mm]	1	1
Rms energy spread [%]	0.1	0.1

MAIN PARAMETERS

Two possible scenarios have been identified for the injector complex. The first scenario remains the baseline, where the 6 GeV beams are injected into the existing Super Proton Synchrotron (SPS) ring or into a new pre-booster ring (PBR). In the second option, an additional high-energy (HE) linac would boost the energy from 6 GeV to 20 GeV and inject the beams directly into the main booster. The injector complex up to 6 GeV can be identical in the two scenarios. Table 1 lists the target parameters at the end of the injector complex for the two options. Another important specification is that the intensity of the electron and positron bunches have to vary randomly from 0 to 100 % depending on the intensity balance between the collider rings. Furthermore, the bunch-by-bunch stability for the injection has to be within 3 %.

Filling Scheme

The filling scheme of the colliders foresees 10 cycles for each species, designated to pre-compensate the charge loss due to collisions, and to always keep the charge imbalance within ±5 %. This operation mode is referred to as bootstrapping [2]. The times necessary for the accumulation and

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Table 2: Times required for the filling from scratch of the collider rings for the most demanding Z-mode. A transmission of 90 % is considering between different accelerators.

Baseline Scenario		**HE Linac Scenario**	
(1) Injector up to 6 GeV		**(1) High-energy linac up to 14 – 20 GeV**	
Bunch charge = 5.55 nC		Bunch charge = 5.00 nC	
2 bunches per RF pulse at 200 Hz		2 bunches per RF pulse at 200 Hz	
(2) SPS or pre-booster ring, Bucket charge = 5.00 nC		(This step is removed in this scenario)	
Accumulation of 755 bunches	1.89 s		
Emittance cooling (damp. time = 0.03 s)	0.1 s		
Ramp up and down time (6 – 20 GeV)	0.28 s		
SPS cycle time	2.29 s		
(3) Top-up booster, Bucket charge = 4.50 nC		**(2) Top-up booster**, Bucket charge = 4.50 nC	
Accumulation of 9060 bunches (12 SPS cycle times)	27.48 s	Accumulation of 9600 bunches	24 s
Emittance cooling (damp. time = 0.1 s)	0.4 s	Emittance cooling (damp. time = 0.1 s)	0.4 s
Ramp-up time (20 – 40.5 GeV)	0.63 s	Ramp-up time (20 – 40.5 GeV)	0.63 s
BR cycle time	28.53 s	BR cycle time	25.03 s
(4) Collider, Bucket charge = 40.5 nC		**(3) Collider**, Bucket charge = 40.5 nC	
10 BR injections per specie of 4.50 nC		10 BR injections per specie of 4.50 nC	
Total filling time Z- mode	570.6 s	Total filling time Z- mode	500.6 s
Luminosity lifetime	1089 s	Luminosity lifetime	1089 s

ramping up in the different stages of the injection are listed in Table 2.

e- SOURCE AND e+/e-LINACS

The latest layout of the FCC-ee injector complex is shown in Figure 1. It foresees two separate linacs for electrons and positrons up to 1.54 GeV. Electrons are accelerated to 6 GeV for both positron production and injection into the SPS or booster ring. Once generated, the positrons are accelerated and injected into the Damping Ring (DR) at 1.54 GeV. Furthermore, the DR must also ensure a delay so that the positron and electron bunches are allocated on consecutive RF buckets in the common linac separated by 2.5 ms during the positron production. To ensure that the collider rings are filled within the filling time specification for the Z-mode, the two low-energy electron and positron linacs have to work at a repetition rate of 200 Hz while the common linac has to work at a repetition rate of 400 Hz (200 Hz for electron bunches and 200 Hz for the positron bunches). The low-energy positron linac is still a work in progress where several aspects still have to be studied in detail. The main goal is to transport and accelerate a positron beam with a high transverse emittance and energy spread, in the order of 10 mm rad and 15 % respectively. Three main types of section have been proposed for the positron linac: solenoids around the RF accelerating structures, a FODO lattice with quadrupoles around the RF accelerating structures and a FODO lattice with quadrupoles between the RF accelerating structures. Simulations up to 200 MeV show a positron yield more than 5 with solenoid channels [3]. It is still an open discussion whether this last option, using solenoidal channel, could be extended, even to 1.54 GeV.

A first conceptual design of the electron source exists and is based on the SwissFEL RF photo-injector [4] and can provide electrons for both ring injection and positron production. Results of preliminary simulations and optimisations have shown that normalized emittance values below 10 mm rad up to 5 nC can be achieved, and even with short bunches up to an rms length of 0.65 mm. This is an important first conclusion because this implies that a DR for the electron beam is not necessary to reduce emittance for the electron bunches. However, the possibility of using DR to stabilise the intensity of the electron bunch is still under discussion, but this option will eventually be put forward after studies of the stability of the electron source and the phase and amplitude jitters of the linacs. Furthermore, the 100% intensity (charge) modulation of the electron and positron charge required for injection into the collider ring could be provided from an optical modulator in the laser system and this possibility is also under investigation.

POSITRON SOURCE

A high positron yield is an extremely important topic for a electron-positron collider like FCC, designed to operate at the extreme end of parameters. In the baseline positron production scheme for FCC-ee, electrons from a drive linac hit a small portion of an amorphous target (e.g. tungsten) and positrons are created through bremsstrahlung and the following pair conversions. The positron beam is created with large divergence and energy distributions, due to the multiple showering and scattering processes. In order to reduce the emittance, the positrons are focused with a strong axial magnetic field produced by the so-called Matching Device surrounding the target [5, 6]. Two options are currently considered for the Adiabatic Matching Device (AMD): the first involves the use of a flux concentrator (FC) based in a pulsed, normal conducting magnet as in the SuperKEKB positron source layout [7] while the second uses an AMD based on high-temperature superconducting (HTS) coils. Preliminary simulations show that the AMD based on HTS

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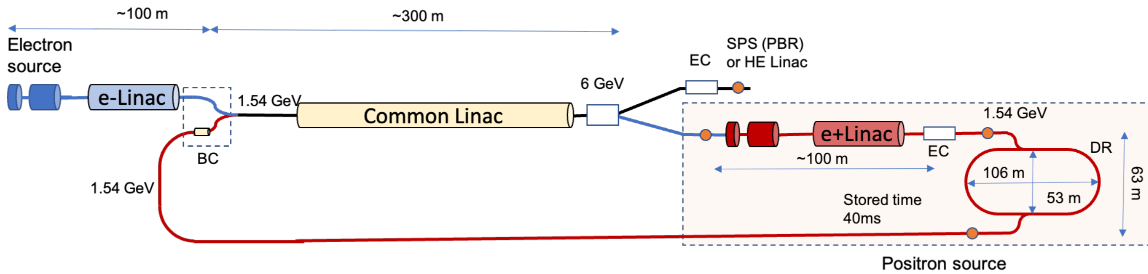

Figure 1: Latest baseline layout of the FCC-ee injector complex. BC: bunch Compressor. EC: Energy Compressor.

coils can provide very high positron yields at the DR (5.1 - 7.2) compared to the AMD based on a FC (3.2 - 4.4) [3]. Nevertheless, in order to achieve an acceptable positron production, the considered target is made of tungsten-rhenium, which gives also a significant flux of unwanted secondary particles, that in turn could generate a too large radiation load on the superconducting coils. The feasibility of such a positron source was assessed by studying the thermal load and long-term radiation damage in the HTS AMD and radiofrequency structures following the target. The results are promising although further studies of shielding and evaluations of the effect of long-term radiation still need to be carried out [8]. Further positron source studies involve the use of axially aligned crystals as radiators. In this scheme, electrons from the driving linac that penetrate the crystal at radiating angles to the axes or planes are channelled and emit a channelling radiation. This radiation provides a large number of softer photons than bremsstrahlung for the following conventional target, reducing the thermal load and increasing the target positron yield [9].

DAMPING RING AND TRANSFER LINES

The DR is necessary to reduce the angular divergence (emittance) of the positron beam to a value appropriate for injection. This is achieved through the process of radiation damping, i.e. the combination of synchrotron radiation in bending fields and wigglers with energy gain in radio-frequency (rf) cavities. The DR is for all intents and purposes part of the positron source because its dynamic aperture, longitudinal and transverse acceptance parameters are the target parameters for the design of the linac and the positron capture. The DR parameters are listed in [1]. The injection time of the 2-bunch must be optimised so that the fast injection kickers do not also affect the stored beam. In addition, the DR should be able to provide the 2.5 ms delay needed of the common linac operation. These two aspects impose stringent boundary conditions for the time separation of the two bunches. This specific problem and the definition of the separation in time of the two bunches still need to be investigated and studied in detail. In order to define the bunch length in the DR and consequently the specifications on the RF system, some analytical calculations on various collective effects were performed. The results, taking into account space charge, intra-beam scattering, longitudinal microwave instability, transverse mode coupling instability, ion effects, electron cloud and synchrotron coherent radiation are presented in this report [10].

P^3 EXPERIMENT

The PSI Positron Production (P^3) is the proposed proof-of-principle experiment for the FCC-ee positron source. The main goal of the experiment is to test novel-approach technology (e.g. HTS solenoids as an AMD), and validate the proposed high positron yield scheme. To this end, it is planned to build a small prototype of the FCC-ee positron source, to be installed in the SwissFEL linac at PSI, where a 6 GeV drive electron beam with the appropriate specifications for positron generation is available. The basic design involves a tungsten target, an AMD based on HTS coils surrounding the target, and two S-band standing-wave cavities surrounded by solenoid fields. In addition, the captured electron and positron beams are separated through a bending magnet, and measurements of total charge, energy distribution and time structure are performed. It should be noted that the baseline design of P^3 has some substantial differences with the FCC-ee injector. First, the drive-linac is operated at 1 Hz repetition rate with a bunch charge of 200 pC. This implies an significantly lower thermo-mechanical stress at the target with respect to FCC-ee, and therefore a cooling system is not strictly needed. In addition, the availability of commercial klystrons and conventional waveguide components determined the choice of the 3 GHz frequency for the RF cavities.

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