

POSITRON SOURCE FOR FCC-ee

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Abstract

The FCC-ee is a high-luminosity, high-precision circular collider to be constructed in a new 100 km tunnel in the Geneva area. The physics case is well established and the FCC-ee operation is foreseen at 91 GeV (Z-pole), 160 GeV (W pair production threshold), 240 GeV (Higgs resonance) and 365 GeV ($t\bar{t}$ threshold). Due to the large 6D production emittance and important thermal load in the production target, the positron injector, in particular the positron source, is one of the key elements of the FCC-ee, requiring special attention. To ensure high reliability of the positron source, conventional and hybrid targets are currently under study. The final choice of the positron target will be made based on the estimated performances. In this framework, we present a preliminary design of the FCC-ee positron source, with detailed simulation studies of positron production, capture and primary acceleration.

INTRODUCTION

Increasing interest in high-intensity and low-emittance positron beams for electron-positron colliders gave rise to different approaches. In the case of positron beams to be injected into circular colliders, the main concern is an optimized 6D emittance, whereas very high intensities are required for linear colliders. These constraints about intensity and emittance have some consequences on the heat load and reliability of the targets. The high-luminosity circular collider FCC-ee will need a low-emittance positron beam with high enough intensity to shorten the injection time. A positron bunch intensity of 2.1×10^{10} particles is required at the injection into a pre-booster ring allowing for a positron yield of $0.5 N_{e^+}/N_{e^-}$ without any safety factor. This value is comparable with the positron yield foreseen at the SuperKEKB.

Two methods are investigated to obtain the required performances. The first one is based on a conventional positron source using high-energy electrons impinging on a thick target with high atomic number Z . The bremsstrahlung radiation of the electrons in the field of the nuclei is converted in e^+e^- pairs. This scheme has been used for all the e^+e^- colliders (ADA, ACO, DCI, SPEAR, ADONE, LEP and also for the first linear collider SLC) [1]. The experience has been mainly successful. However, due to the high number of

electrons in the short bunch of SLC, the breakdown analysis of the used target led to a limitation in the deposited power density expressed in J/g [2]. Its maximum value (PEDD), for tungsten targets, is about 35 J/g. Such limitation has some consequences on the incident electron beam size and the target thickness limitations. A second approach is based on the production of a large number of photons in thin crystal targets oriented on their main axes. Electrons propagating in the crystal at glancing angles to the axes are channeled and emit a large number of soft photons due to the collective action of a large number of nuclei [3]. Such method has been successfully tested at CERN and KEK [4–7]. These investigations led to a concept of so-called hybrid positron source [8] associating a thin oriented crystal with an amorphous converter and a sweeping magnet in between to sweep off the charged particles emitted in the crystal, allowing only the photons to hit the amorphous converter. In this context, the hybrid scheme has been adopted by CLIC as a baseline for the unpolarized positron source [9]. For the FCC-ee positron source, the two options (conventional and hybrid) are under consideration.

FCC-ee INJECTOR COMPLEX

In the current baseline [10], the injector complex for the FCC-ee consists of a 6 GeV linac with the Damping Ring (DR) at 1.54 GeV to damp the emittance of both electron and positron beams. The beams are accelerated from 6 to 20 GeV in the pre-booster synchrotron ring and then to full energy in the booster synchrotron ring. Due to the accumulation in the main collider, the required linac bunch intensity is 2.1×10^{10} particles/bunch for both species. The S-band normal conducting linac working at 100-200 Hz with 1 or 2 bunches per pulse is considered to provide the requested performances. In this context, more information on the pre-injector chain and the injection schemes is given elsewhere [11–13]. As an alternative option for the FCC-ee injector, a 20 GeV linac is proposed to provide the direct injection into the booster ring.

Positron Source

For positron production, the same 6 GeV electron linac is used with a higher bunch intensity of 4.2×10^{10} electrons/bunch at an energy of 4.46 GeV. A bypass line for positron generation and primary acceleration is under consideration in order to avoid the drawbacks associated with

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the target having a hole for a passage of the electron beam. The positron beam emittance is reduced in the the DR at an energy of 1.54 GeV and the beam is then transferred back to the linac for further acceleration and injection into the pre-booster ring.

The possibility of using a 20 GeV linac as the FCC-ee injector and so the higher-energy incident beam for positron production (18.46 GeV instead of 4.46 GeV) represents a real advantage for positron production as the positron yield is increasing with the incident energy. For the conventional amorphous targets, we have the known example of the SLC, where the positrons were obtained with a 33 GeV incident electron beam on a tungsten $6X_0$ thick target. At present, the positron production rate obtained at the SLC is considered as a world record for the existing accelerators (about $2.5 N_{e^+}/N_{e^-}$ injected in the DR [1]). Preliminary simulations for the FCC-ee show that with the 18.46 GeV electron beam, the total positron yield after the target is $39 N_{e^+}/N_{e^-}$ compared to $11 N_{e^+}/N_{e^-}$ obtained with the 4.46 GeV incident beam energy (target thickness is chosen to maximize the positron production). Using oriented crystals the situation is even more attractive. Experiments at CERN (WA 103) have shown [14] that for a 8 mm thick tungsten crystal aligned on its $\langle 111 \rangle$ axis the enhancement crystal/amorphous target was more than a factor 3 for an incident energy of 20 GeV. With energy increased from 10 to 20 GeV the enhancement factor of 2 was measured for the crystal target. For these energies only the Bethe-Heitler mechanism could be involved in positron production. However, increasing further the incident energy could bring more significant enhancement (using the well collimated photons at energies much larger than 20 GeV) making profit of the pair creation in strong field [15].

POSITRON PRODUCTION AND CAPTURE

The FCC-ee positron source is based on the target converter using a metal target in the conventional scheme or compound target consisting of a crystal which serves as a radiator of photons (main part of the energy spectrum between MeV and tens of MeV) followed by the amorphous metal target used for positron generation in the hybrid scheme. The capture section is composed of an Adiabatic Matching Device (AMD) [16] followed by the capture linac embedded in a DC solenoid magnetic field used to accelerate the beam until about 200 MeV. At this energy the positrons can pass to the quadrupole focusing system and be further accelerated up to the 1.54 GeV (energy of the DR). For the capture linac L-band and S-band RF structures are under study providing that larger iris apertures allow larger transverse acceptance of the positrons.

Production Target

The materials with high Z like tungsten ($Z=74$) are preferable for the positron converters. In the real experiments the tungsten-rhenium ($W_{75}-Re_{25}$) alloy targets are usually

used. After the optimization studies regarding the positron yield and deposited power (see Fig. 1), a 16 mm thick target made of tungsten has been used to simulate the production of the positrons in the conventional scheme and 1.4 mm tungsten crystal followed by the 12 mm thick amorphous tungsten target in the hybrid scheme. This choice provides the maximum positron yield while keeping the deposited power at an acceptable level of 2.1 kW and 0.8 kW in the case of conventional and hybrid scheme, respectively (see Fig. 1). Peak Energy Deposition Density (PEDD) with 2 bunches of electrons (6.7 nC/bunch) is expected to be 17 J/g and 3 J/g (for the beam size of 0.5 mm on the target) in the case of conventional and hybrid scheme, respectively. Even though these values stay well below the 35 J/g limit imposed by the SLC target breakdown, a detailed analysis of the thermal fatigue caused by the heat cycling load from the pulsed operation should be performed.

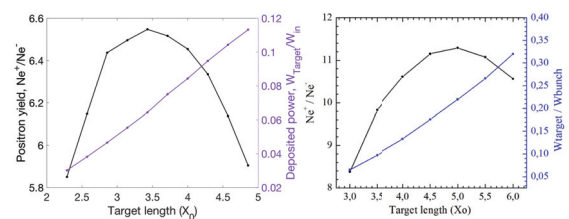


Figure 1: Optimization of the target-converter thickness for the conventional (right) and the hybrid (left) schemes. Radiation length of the tungsten X_0 is 0.35 cm.

Capture Section and Primary Acceleration

The capture section design for both studied schemes is based on the AMD made of the tapered solenoid field and used for the phase-space transformation of the positron beam at the target (with large transverse divergence) in order to match the acceptance of the capture linac. Flux Concentrator (FC) is usually used as a device which forms adiabatically decreasing magnetic field. Figure 2 shows the example of such transformation in the case of hybrid scheme.

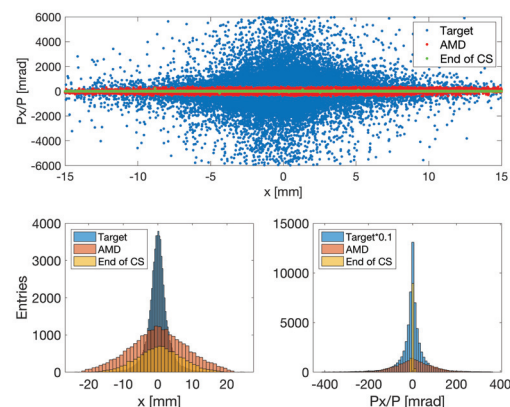


Figure 2: Positron emittance at the exit of the target, the AMD and the capture section at ~ 200 MeV.

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Several models of the FC have been designed and studied for the FCC-ee giving the full 3D magnetic field map used for the simulations. The FC used in the simulation is 14 cm long with a longitudinal magnetic field starting at 5-7 T and adiabatically decreasing down to 0.5-0.7 T. The front and rear aperture diameter of the FC is 8 mm and 44 mm, respectively. For the positron yield calculation, a gap between the target end and the nose of the FC of 2 mm was assumed. Preliminary studies for the ILC indicate a significant dependence of the yield on the detailed shape of the magnetic field at that location [17].

For these studies, the capture linac for the the hybrid scheme is made of the 1.5 meter long 17 MV/m 2 GHz L-band structures while for the conventional scheme the 20 MV/m 2856 MHz large aperture S-band cavities of the 3 meter long are employed. The whole capture linac is encapsulated inside a solenoid with the axial magnetic field equals to 0.5-0.7 T in order to focus the positrons and avoid losses until their transverse momentum is sufficiently reduced.

Figures 3 and 4 (left) shows the longitudinal distribution of the positrons brought to the energy of ~200 MeV for the hybrid and conventional schemes, respectively.

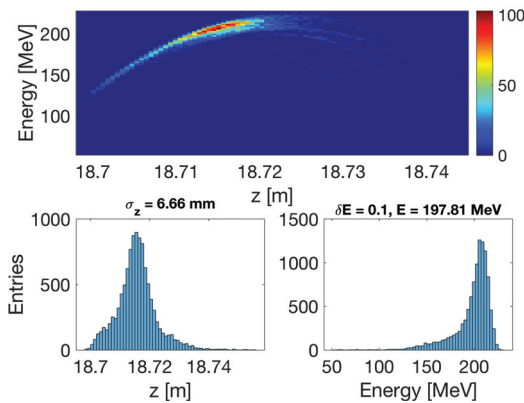


Figure 3: Longitudinal phase space of the positrons at the end of the capture linac for the hybrid scheme.

At this stage, an energy-longitudinal position cut around the highest density of positrons made within the DR acceptance [13] allows defining the accepted positron yield¹. In addition, Figure 4 (right) illustrates the dependence of the accepted positron yield on the FC peak magnetic field and the DC solenoid field of the whole capture section. As one can see, the increase in the accepted positron yield becomes less important for the DC solenoid field above 1 T. On the other hand, from the technical point of view, the field strength of up to 0.7-0.8 T should be still feasible with the warm technology. As for the choice of the FC peak field, it can be taken up to 7-8 T. Its further increase doesn't affect the positron yield significantly but makes the design and operation of the FC much more complicated.

¹ Different values of the energy-longitudinal position cut are used for the conventional and hybrid schemes but both within the acceptance of the damping ring.

The main results of the simulations are summarized in Table 1 taking into account the acceptance of the DR.

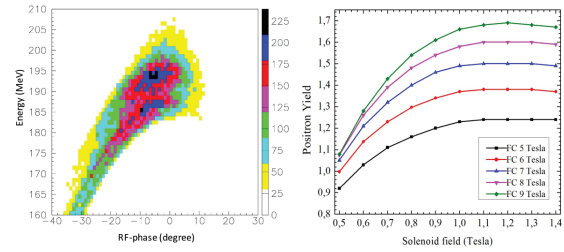


Figure 4: Longitudinal phase space of the positrons at the end of the capture linac for the conventional scheme (left). Accepted positron yield as a function of the DC solenoid field for different values of the FC peak magnetic field (right).

Table 1: Results for the Positron Production and Capture Simulations

Parameters	Conv. scheme	Hybrid scheme ²
Target deposited power	2.1 kW	0.8 kW
PEDD	17 J/g	3 J/g
$B_{max} = 5 \text{ T}, B_{DC} = 0.5 \text{ T}$		
Mean energy	190 MeV	197 MeV
Accepted yield	$1.1 N_{e^+}/N_{e^-}$	$0.9 N_{e^+}/N_{e^-}$
Emittance $\epsilon_{x/y}$	$17 \mu\text{m} (1\sigma)$	$14 \mu\text{m} (2\sigma)$
Energy spread	3.5 %	11 %
Bunch length (σ_z)	4 mm	7 mm
$B_{max} = 7 \text{ T}, B_{DC} = 0.7 \text{ T}$		
Mean energy	190 MeV	198 MeV
Accepted yield	$1.3 N_{e^+}/N_{e^-}$	$1.1 N_{e^+}/N_{e^-}$
Emittance $\epsilon_{x/y}$	$21 \mu\text{m} (1\sigma)$	$16 \mu\text{m} (2\sigma)$
Energy spread	3.9 %	10 %
Bunch length (σ_z)	4 mm	7 mm

CONCLUSIONS

Positron sources are complex devices, where each stage (production, capture, acceleration, injection strategy) has an impact on the final efficiency of the system. Therefore, the final multi-parameter optimization has to be performed for the whole chain. Two scenarios using the conventional and hybrid targets are being studied for the positron source at FCC-ee. Presented studies show that both provide the comparable positron yield ($\sim 1 N_{e^+}/N_{e^-}$) accepted by the DR. However, as far as reliability of the target is concerned, the hybrid scheme is more attractive allowing lower deposited power and PEDD in the production target. In this case, the design of the target together with its cooling system and evaluation of the thermal load in the target including peak stress and fatigue limit are of great importance. Further optimization of the positron production, capture and simulation of the beam transport to the DR are underway.

² The values are given for the amorphous target-converter installed after the crystal target.

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