ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL094

BENCHMARKING THE FCC-ee POSITRON SOURCE SIMULATION TOOLS USING THE SUPERKEKB RESULTS *

F. Alharthi†[1], I. Chaikovska, R. Chehab, CNRS-IJCLab, Paris-Saclay U.,Orsay, France
[1]also at KACST, Riyadh, Saudi Arabia
Y. Zhao, A. Latina, CERN, Geneva, Switzerland
Y. Enomoto, F. Miyahara, High Energy Accelerator Research Organization (KEK) Japan
V. Mytrochenko, NSC Kharkiv Institute of Physics and Technology, Ukraine

Abstract

For the Future Circular Collider (FCC-ee), particular attention is drawn to the crucial role of the positron source. Two positron production schemes are considered for the FCC-ee: the conventional scheme and the crystal-based (hybrid) scheme that involves channelling radiation in the oriented crystals. A start-to-end simulation toolkit should be developed to design and optimize positron production and capture by considering the positron injector parameters, including the electron drive beam and final system acceptance. This paper presents the first results of benchmarking the FCC-ee positron source simulation tools using the SuperKEKB positron source currently in operation. The model starts with the production of positrons and target studies in Geant4. Then, the RF-Track code is used to capture and track the generated positrons through the capture section composed of a matching device and several accelerating structures embedded in the solenoid field to accelerate the positrons up to 120 MeV. After that, the positrons are further accelerated up to the energy of the Damping Ring (1.1 GeV). Finally, the SuperKEKB capture system is applied to the FCC-ee positron injector within the framework of the design studies.

INTRODUCTION

The conceptual design of the FCC-ee is continuously developing [1], more specifically on the pre-injector side to fulfil the four operation modes *Z, W, H* bosons and $t\bar{t}$ [2]. The latest baseline layout of the pre-injector considered the Z-operation mode as a reference since it demands the highest current of 1.3 A stored in the collider. Thus, a positron bunch intensity of 4 nC is required at the injection into a Damping Ring (DR), allowing for an accepted positron yield of 1.4 N_{e^+}/N_{e^-} assuming the maximum available electron bunch charge and a factor of 2 as a safety margin. The pre-injector has to operate at 200 Hz with two bunches per RF pulse. The positron bunches are produced within a target. Two positron production schemes are considered to ensure high performance of the positron source: *Conventional and Hybrid* [3]. Validation of the FCC-ee positron source simulation tools is required in order to achieve a realistic and reliable design. In this context, the SuperKEKB positron source currently in operation is considered for the benchmarking studies.

Hence, in this paper, we briefly present the current design of the SuperKEKB positron source. We then present the validation of the FCC-ee positron source simulation tools performed using the SuperKEKB positron source results. Finally, we investigate the application of the SuperKEKB capture system for the FCC-ee positron source.

SUPERKEKB POSITRON SOURCE

SuperKEKB is an electron-positron collider holding the world's highest luminosity record of producing B meson pairs [4]. Moreover, the SuperKEKB positron source is the world's highest-intensity positron source currently in operation, making it very suitable for validating the FCC-ee positron source simulation tools. The positron source at SuperKEKB is based on the conventional production scheme. Under this scheme, a pulse of an electron beam (two bunches of 10 nC each) generated by a thermionic gun strikes a thick tungsten target to generate a positron beam [5]. The requirement on the positron beam imposed by the SuperKEKB collider is 4 nC per bunch injected in the collider [6]. The last run in 2022 showed that the positron bunch charge at the end of the injector linac is 3.5 nC, which is very close to the nominal value. The target design is a 14 mm thick cylinder with a 2 mm radius made of tungsten placed inside a copper holder surrounded by a cooling system [7]. To carry out a pulse-by-pulse operation of the positron and electron injection, a 1 mm hole is bored at the center of the copper holder in order for the electron beam to pass onto the collider ring. At the same time, the tungsten target is positioned with a 3.5 mm offset relative to the electron beam axis. A pulsed steering magnet upstream from the target is used to guide the primary electron beam 2 mm off-axis to impinge on the target, as shown in Fig. 1.

The generated positron beam has a substantial angular divergence due to electromagnetic shower processes and requires an immediate capture system. The capture system is composed of an Adiabatic Matching Device (AMD), consisting of a Flux Concentrator (FC) and Bridge Coil [8], followed by six Large Aperture S-band (LAS) accelerating structures embedded in a solenoid to accelerate the positron beam up to 120 MeV. More details about the capture linac can be found in [9]. In this study, we focus on the simulation results up to the end of the capture section.

---

* We acknowledge the support from ANR (Agence Nationale de la Recherche) Grant No: ANR-21-CE31-0007. This work was done under the auspices of CHART Collaboration (Swiss Accelerator Research and Technology, http://www.chart.ch).

† falharthi@kacst.edu.sa

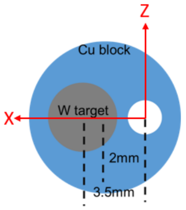


Figure 1: Target layout seen by the incoming electron beam. The electron beam axis is at the center. To produce the positron beam, the electron beam is steered 2 mm off-axis and impinges on the target located at 3.5 mm off-axis.

Table 1: Parameters of the Electron Beam of SuperKEKB Positron Source

Beam parameters	Value	Unit
Number of simulated particles	10000	
Energy	2.9	GeV
Beam center (x,y)	(2,0)	mm
Beam size (σ_x,σ_y)	(0.5, 0.8)	mm
Bunch length (RMS)	1.26	mm

VALIDATION OF THE FCC-ee POSITRON SOURCE SIMULATION TOOLS

The FCC-ee positron source simulation model consists of two stages: target studies including positron production performed in the GEANT4 toolkit [10] and positron beam capture and tracking in a capture linac using RF-Track [11]. In comparison, the SuperKEKB simulation tool is a combination of two codes: EGS5 [12] for positron production and General Particle Tracer (GPT) [13] for positron beam capture and tracking. The two models were compared based on energy deposition in the target, positron beam transverse and longitudinal properties, and positron yield. While the current study focused on the positron yield, future work will explore the complete beam dynamics and characterizations of the positron beam, which will be discussed in a forthcoming paper. Positron yield is defined as the number of generated positrons normalized to the number of incoming electrons evaluated at different locations along the injector up to the DR, where the final accepted yield is evaluated ($\eta = N_{e^+}/N_{e^-}$). The parameters used for the simulations are presented in Table 1. The layout of the SuperKEKB target in GEANT4 is shown in Fig. 2.

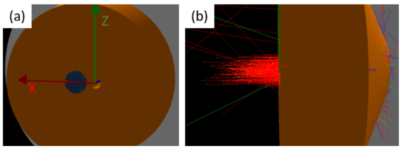


Figure 2: SuperKEKB target geometry is implemented in GEANT4. (a) The target is depicted in blue, surrounded by the copper holder. (b) Side view. Illustration of the electron beam – target interaction. The electron beam is shown in red.

In the current design, the FC is placed at 2 mm from the target exit. The FC is a pulsed magnet operated at 12 kA with front and rear aperture diameters of 7 mm and 52 mm, respectively. A Bridge Coil (DC solenoid) is added to enhance the magnetic field strength. In this simulation, we used realistic 3D magnetic field maps provided by SuperKEKB. The AMD field along the positron beam axis is presented in Fig. 3.

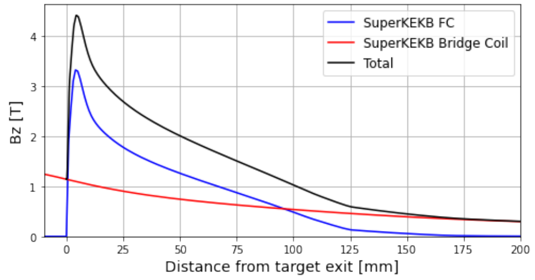


Figure 3: SuperKEKB AMD field profile along the beam axis. The target exit is located at z = 0 mm. The field at the target exit is 1.1 T.

Finally, the six LAS accelerating structures immersed in the solenoid field were simulated. The first two LAS operate in deceleration mode as the simulation and operation show lower energy spread, allowing maximum accepted yield at the DR. The longitudinal phase space of the positron beam is presented in Fig. 4. The presented simulations show a very good agreement with the SuperKEKB model in terms of positron yield (see Fig. 5). Validation of the FCC-ee simulation tools with experimental data taken at SuperKEKB will be described in the forthcoming paper.

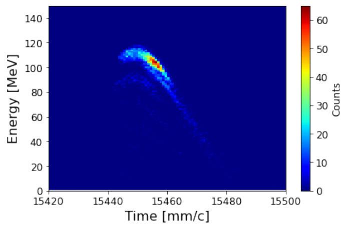


Figure 4: Positron beam longitudinal phase space at the end of the capture section.

FCC-ee POSITRON SOURCE SIMULATIONS

In this study, we used *the conventional* scheme for positron production. Under this scheme, a 6 GeV electron beam strikes a 17.5 mm tungsten target. Table 2 presents the primary electron beam parameters. A positron production rate of 13.7 N_{e^+}/N_{e^-} was obtained after the target. To capture the generated positron beam, two options for the AMD were considered: the FC as the baseline option and the High-Temperature Superconducting (HTS) solenoid [3] option. The conceptual design and prototyping of the HTS solenoid were performed at the Paul Scherrer Institute (PSI) [14]. The

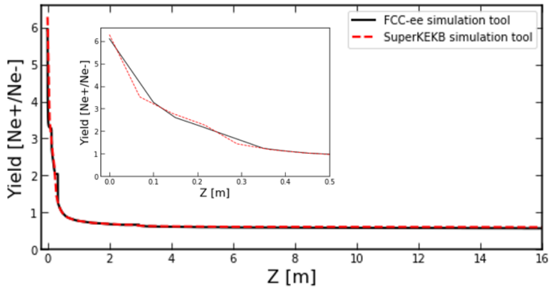


Figure 5: Comparison of the two simulation models (FCC-ee and SuperKEKB) in terms of the positron yield along the capture section.

Table 2: Parameters of the Electron Beam of the FCC-ee Positron Source

Beam parameters	Value	Unit
Number of simulated particles	10000	
Energy	6	GeV
Beam size (σ_x,σ_y)	0.5, 0.5	mm
Bunch length (RMS)	1	mm
Energy spread (RMS)	0.1	%

final design of the FC is under development. In this context, we initiated the optimization studies by using the realistic 3D field map of the SuperKEKB AMD. As a result, a positron yield of 7.5 N_{e^+}/N_{e^-} was found after the AMD section.

Two types of Traveling Wave (TW) structures for the capture linac were studied: a 2 m long LAS SuperKEKB-like structure and a 3 m long large Aperture L-band structure designed by CERN to provide a larger transverse acceptance [15] (see Table 3). In both cases, we assumed a gradient of 20 MV/m to reach 200 MeV positron beam energy at the end of the capture linac. Moreover, the RF phases were optimized to maximize the positron yield and reach the desired value of the energy.

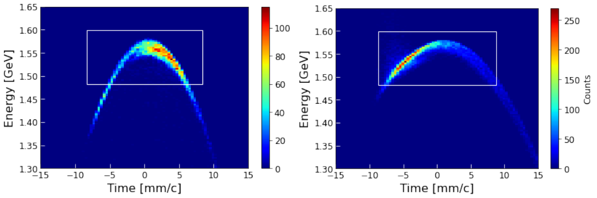
Table 3: TW Structures Parameters

Parameter	S-band	L-band
Frequency [GHz]	2.856	2
Phase advance [degree]	$2\pi/3$	$9\pi/10$
Length [m]	2.064	3.24
Aperture (2a) [mm]	30	60
Gradient [MV/m]	20	20
Number of structures	6	4

The positron tracking simulations show that the higher positron yield was obtained with the L-band structure due to its larger aperture. However, the energy spread was much higher than the LAS structure-based capture system. A summary of the simulation results is shown in Table 4. More studies are ongoing to optimize the positron yield and emittance in the capture linac.

Acceleration of the positron beam after the capture section from ~ 200 MeV to 1.54 GeV (the energy of the DR) was modelled using an analytical formula. $\Delta E = \Delta E_0 \cdot \cos(2\pi f \cdot \Delta t)$, where $\Delta E_0 = 1.54\ \text{GeV} - E_{\text{ref}}$ is the maximum energy gain, the reference particle energy is around 200 MeV, f = 2.856 GHz (LAS) or 2 GHz (L-band) is the RF frequency and $\Delta t = t - t_{\text{ref}}$ is the time difference from the reference particle. For the positron linac we also investigated two TW structure options.

At the DR, the accepted positron yield was estimated for the positrons within an energy-time window (± 58.5 MeV, 17.5 mm/c or 16.7 mm/c) around 1.54 GeV for the LAS and the L-band RF structures-based positron linac respectively. The longitudinal phase space of the positron beam at the end of the positron linac, including the window cut, is presented in Fig. 6. Simulation results are summarized in Table 4. A more realistic estimate of the accepted positron yield will be made using the positron tracking simulations in the positron linac and the DR.



(a) (b)

Figure 6: Comparison of the longitudinal phase space of the positrons at the entrance of the DR for two options of the positron linac: based on the LAS structure (a) or the L-band structure (b). The white rectangle represents the energy-time window cut. The reference time is set at 0.

Table 4: Summary of the Simulation Results

Positron yield (N_e+/N_e-)	S-band	L-band
After the target	13.7	
After the AMD	7.5	
At the end of capture linac	1.7	3.2
Accepted Yield at DR	1.3	2.5

SUMMARY AND OUTLOOK

This paper presents the FCC-ee positron source simulation model, including benchmarking the simulation tools with the SuperKEKB positron source. Considering the positron yield as a figure of merit, the comparison of the two models showed very good agreement. After the validation stage, in the context of the FCC-ee AMD studies, we investigated the application of the SuperKEKB capture system to the FCC-ee positron source. We considered two options for the capture and positron linacs using LAS and L-band RF structures. The presented study shows that a higher value of positron yield of 2.5 N_{e^+}/N_{e^-} accepted by the DR could be obtained by using the L-band RF structures. Further optimizations of positron capture are underway to better match the positron bunch 6D phase space to the positron linac and the DR.

REFERENCES

[1] M. Benedikt *et al.*, "Future Circular Collider: Conceptual Design Report Vol. 2", accepted for publication in *EPJ ST*, CERN-ACC-2018-0057, 2018.

[2] P. Craievich *et al.*, "The FCCee Pre-Injector Complex", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 2007–2010. `doi:10.18429/JACoW-IPAC2022-WEPOPT063`

[3] I. Chaikovska *et al.*, "Update on the FCC-ee Positron Source Design Studies", presented at the 14th International Particle Accelerator Conf. (IPAC'23), Venice, Italy, May 2023 paper MOPL095, this conference.

[4] Y. Ohnishi, "SuperKEKB Luminosity Quest", in *Proc. eeFACT'22*, Frascati, Italy, Sep. 2022, pp. 1–6. `doi:10.18429/JACoW-eeFACT2022-MOXAT0103`

[5] T. Kamitani *et al.*, "SuperKEKB Positron Source Construction Status", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 579–581. `doi:10.18429/JACoW-IPAC2014-MOPRI004`

[6] M. Satoh *et al.*, "Commissioning Status of SuperKEKB Injector Linac", in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 4152–4154. `doi:10.18429/JACoW-IPAC2016-THPOY027`

[7] L. Zang *et al.*, "Positron Yield Optimization by Adjusting the Components Offset and Orientation", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 576–578. `doi:10.18429/JACoW-IPAC2014-MOPRI003`

[8] Y. Enomoto, K. Abe, N. Okada, and T. Takatomi, "A New Flux Concentrator Made of Cu Alloy for the SuperKEKB Positron Source", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 2954–2956. `doi:10.18429/JACoW-IPAC2021-WEPAB144`

[9] S. Matsumoto, T. Higo, K. Kakihara, T. Kamitani, and M. Tanaka, "Large-aperture Travelling-wave Accelerator Structure for Positron Capture of SuperKEKB Injector Linac", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 3872–3874. `doi:10.18429/JACoW-IPAC2014-THPRI047`

[10] S. Agostinelli *et al.*, [GEANT4], *Nucl. Instrum. Meth. A*, **506**, 250-303 (2003) `doi:10.1016/S0168-9002(03)01368-8`

[11] A. Latina, "RF-Track: Beam Tracking in Field Maps Including Space-Charge Effects, Features and Benchmarks", in *Proc. LINAC'16*, East Lansing, MI, USA, Sep. 2016, pp. 104–107.

[12] H. Hirayama *et al.*, "The EGS5 Code System", `https://rcwww.kek.jp/research/egs/index.html`

[13] S.B. van der Geer and M.J. de Loos, "General particle tracer", `http://www.pulsar.nl/gpt`

[14] M. Duda *et al.*, "HTS solenoids for the PSI Positron production project in the context of the CHART FCC-ee injector study"presented at the FCC Week 2022, Paris, France, May 2022.

[15] H. W. Pommerenke *et al.*, "RF Design of Traveling-Wave Accelerating Structures for the FCC-ee Pre-injector Complex", in *Proc. LINAC'22*, Liverpool, UK, Aug.-Sep. 2022, pp. 707–710. `doi:10.18429/JACoW-LINAC2022-THPOJO08`