ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL096

USE OF A SUPERCONDUCTING SOLENOID AS A MATCHING DEVICE FOR THE COMPACT LINEAR COLLIDER POSITRON SOURCE

Y. Zhao*, S. Doebert, A. Latina, J. Olivares[1], CERN, 1211 Geneva 23, Switzerland
[1]also at University of Valencia, Valencia, Spain

Abstract

A matching device with a strong magnetic field is used to capture positrons in the positron source of future e^+e^- colliders such as the Compact LInear Collider (CLIC) and the Future Circular Collider (FCC-ee). Compared to conventional normal conducting (NC) matching devices such as a quarter wave transformer or a flux concentrator, superconducting (SC) solenoids can have a much higher peak field, improving the capture efficiency and the positron yield. In this paper, we tested the latest high temperature superconducting (HTS) solenoid field, which is designed for the FCC-ee positron source, as the matching device in the simulation of the CLIC positron soruce. An analytic SC solenoid field was simulated and the coil parameters were optimised for maximum positron yield.

INTRODUCTION

For positron sources, the matching device plays an important role in capturing the positrons generated from the target, due to its strong magnetic field. With the development of superconductive (SC) solenoid technology, especially the high-temperature superconducting (HTS) solenoid, it has become possible to use SC magnets as matching devices. Compared to conventional matching devices such as a quarter wave transformer (QWT) or a flux concentrator (FC), an SC solenoid can provide a much higher peak magnetic field and improve the positron yield significantly. In the following, we will discuss the possibilities of using an SC matching device for the CLIC positron source [1–3].

The schematic layout of the CLIC positron source with a SC matching device is presented in Fig. 1. The simulation of the CLIC positron source is the same as described in the previously published paper [3], except for the new SC matching device and a few parameters that are slightly reoptimised, such as the electron spot size and the RF gradients and phases.

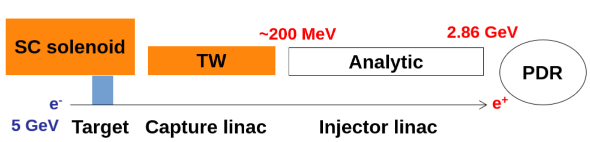

Figure 1: Schematic layout of the CLIC positron source.

The primary electron beam parameters are summarised in Table 1, for different collision energy stages. The target material is assumed to be amorphous tungsten, and the target thickness is 18 mm. To improve the positron yield, the target is assumed to be placed inside the bore of the SC solenoid, with the position of the exit face optimised for maximum positron yield. The capture linac comprises 11 travelling wave (TW) RF structures, working in $2\pi/3$ mode, with a frequency of 2 GHz and an aperture of 20 mm radius. To simplify the design of the CLIC positron source, the average gradient is fixed to be 20 MV/m in the simulation. The TW structures are assumed to be surrounded by normal conducting (NC) solenoids providing a 0.5 T uniform magnetic field. The injector linac is longitudinally simulated with an analytic calculation of the positron energy up to 2.86 GeV:

$$\Delta E = (2.86\,\text{GeV} - E_{\text{ref}}) \cdot \cos\left[2\pi f \cdot (t - t_{\text{ref}})\right] , \quad (1)$$

where E_{ref} and t_{ref} are the energy and time of the reference particle, which is optimised for maximum positron yield. At the end of the injector linac, positrons must be matched to the pre-damping ring (PDR), with an energy acceptance of 1.2% and a time window of 20 mm/c. The positron bunch charge required at the PDR entrance is ~0.8 nC for the 380 GeV energy stage and ~0.6 nC for the 3 TeV energy stage[1], including a 20% safety margin. Geant4 [4] is used to simulate the interactions between the primary electrons and the target. A Gaussian function is used to generate the initial distribution of electrons at the target entrance in Geant4. RF-Track [5] is used to simulate the beam tracking in the matching device and the capture linac.

Table 1: Primary Electron Beam Parameters for Different Collision Energy Stages

Parameters	380 GeV	3 TeV
Beam energy	5 GeV	
Energy spread (RMS)	0.1%	
Normalised emittance (RMS), $\epsilon_{x,y}$	80 mm·mrad	
Bunch length (RMS)	1 mm	
Number of bunches per pulse	352	312
Repetition rate	50 Hz	

TEST OF FCC-EE HTS SOLENOID

An HTS solenoid matching device is designed by the Paul Scherrer Institute (PSI) for the FCC-ee positron source [6–10]. It is found that the HTS solenoid can improve the FCC-ee positron yield by ~50%, compared with a normal conducting flux concentrator [8, 9].

The same HTS solenoid magnetic field, as used for the FCC-ee positron source, is applied to the CLIC positron source to test the improvement in the positron yield. The

* yongke.zhao@cern.ch

[1] For the CLIC positron source, all the parameters and results of the 1.5 TeV energy stage are the same with the 3 TeV energy stage.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL096

position of the target exit face is reoptimised for maximum positron yield. The optimised positron yields, accepted by the PDR, are summarised in Table 2. The target position refers to the longitudinal position of the target exit face with regard to the peak field. The spot size of the electron beam is also slightly reoptimised to improve the positron yield, while the peak energy deposition density (PEDD) in the target is always required to be well below 35 J/g [11]. The improvements of using such an HTS solenoid, on the positron yield, compared with using the conventional flux concentrator as the matching device, are also presented in the table. Two types of flux concentrators, with linearly tapered or non-linearly tapered chamber shapes, are designed for the CLIC positron source [12]. In the simulation and comparison, we always use the type with a linearly tapered chamber shape, which is more conventional and gives a higher peak field and higher positron yield.

Table 2: Results of Simulation with the FCC-ee HTS Solenoid Matching Device for Different Collision Energy Stages

Parameters	380 GeV	3 TeV
Electron beam spot size	1.75 mm	1.15 mm
Target exit face position	80 mm	70 mm
PEDD in target	32.8 J/g	33.5 J/g
Positron yield	2.90	3.48
Yield improvement	29%	27%

ANALYTIC SC SOLENOID FIELD

To further optimise the positron yield, a simple cylindrical SC solenoid winding with a rectangular cross-section is assumed for the coils of the matching device. The on-axis magnetic field of such a matching device can be analytically expressed by the following formulæ [13]:

$$B_z = \frac{1}{2} J a \{F(\alpha, \beta_1) + F(\alpha, \beta_2)\},$$

$$F(\alpha, \beta) = \mu_0 \beta \ln \frac{\alpha + \sqrt{\alpha^2 + \beta^2}}{1 + \sqrt{1 + \beta^2}},$$

$$\alpha = b/a, \qquad \beta_1 = (l - z)/a, \qquad \beta_2 = (l + z)/a,$$

where, J is the average overall current density, a and b are the inner and outer radii of the solenoid, l is the half length of the solenoid. In the case of negative β_1 or β_2, which means that the point is beyond the ends of the coils, $F(\alpha, -\beta) = -F(\alpha, \beta)$ is used.

The positron yield obtained with the analytic SC solenoid field is highly consistent with the realistic FCC-ee HTS solenoid field, assuming that the same coil parameters are used, as can be seen in Table 3. The electron beam spot size and the target position are also kept the same. The current density used for the analytic field is scaled to have the same peak field with the realistic field, given that there are some gaps between the coils in the realistic HTS solenoid design.

The coil parameters are optimised to search for the maximum positron yield, using the Nelder-Mead Simplex method [14] implemented in GNU Octave [15]. To simplify the design of the CLIC positron source, the same SC solenoid matching device is assumed for different energy stages in the optimisation. To make the optimised results more practical, the parameters are constrained to be not much larger than the design values. The peak field is also constrained to be no larger than 20 T. As a result, the optimised parameters and the positron yields are summarised in Table 4. The improvements in the positron yield, compared to using the conventional tapered flux concentrator as the matching device, are also presented in the table.

Table 3: Results of Simulation with An Analytic SC Solenoid with the Same Coils Parameters as the Realistic FCC-ee HTS Solenoid Matching Device

Parameters	Realistic HTS	Analytic SC
Coils inner radius, a	60 mm	
Coils outer radius, b	115 mm	
Coils half-length, l	32.5 mm	
Coils current density, J	630 A/mm^2	606 A/mm^2
Positron yield (380 GeV)	2.90	2.90
Positron yield (3 TeV)	3.48	3.48

Table 4: Results of Simulation with the Optimised Analytic SC Solenoid Matching Device for Different Collision Energy Stages

Parameters	380 GeV	3 TeV
Coils inner radius, a	65 mm	
Coils outer radius, b	135 mm	
Coils half-length, l	35 mm	
Coils current density, J	616 A/mm^2	
Electron beam spot size	1.70 mm	1.10 mm
Target exit face position	92 mm	83 mm
PEDD in target	34.0 J/g	34.0 J/g
Positron yield	2.97	3.56
Yield improvement	33%	30%

The transverse beam performance at the end of the capture linac of the positrons accepted by the PDR are listed in Table 5, while the longitudinal performance at the end of the injector linac of positrons accepted by the PDR are summarised in Table 6.

Table 5: Transverse Beam Performance at the End of the Capture Linac of Positrons Accepted by the PDR with the Optimised Analytic SC Solenoid Matching Device for Different Collision Energy Stages

Transverse performance	380 GeV	3 TeV
Beam size (RMS)	7.2 mm	6.8 mm
Normalised emittance (RMS), $\epsilon_{x,y}$	8.4 mm	8.0 mm

The longitudinal phase space at the end of the capture linac and at the end of the injector linac of all positrons, for the 380 GeV energy stage, are presented in Fig. 2 and

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL096

Table 6: Longitudinal Beam Performance at the End of the Injector Linac of Positrons Accepted by the PDR with the Optimised Analytic SC Solenoid Matching Device for Different Collision Energy Stages

Longitudinal performance	**380 GeV**	**3 TeV**
Mean energy	2.86 GeV	
Energy spread	0.5%	0.6%
Bunch length	2.1 mm	2.0 mm

Fig. 3, respectively. A red box is also drawn on the latter plot indicating the window of the PDR acceptance.

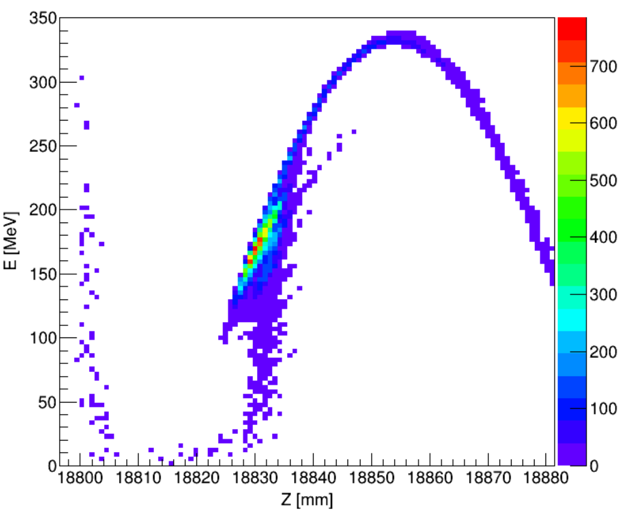

Figure 2: Longitudinal phase space at the end of the capture linac of all positrons with the optimised analytic SC solenoid matching device.

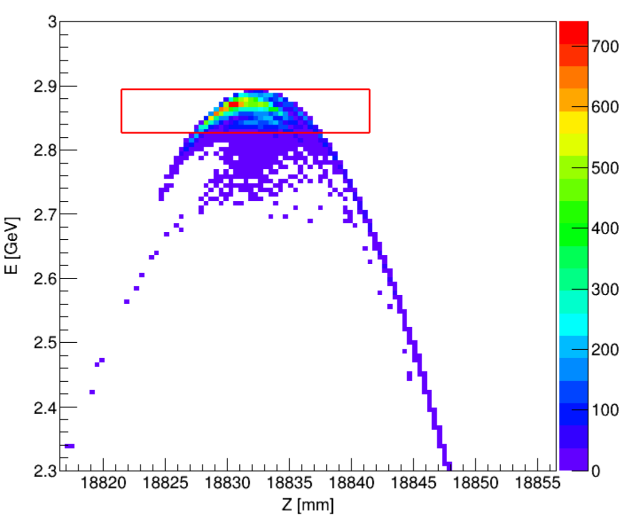

Figure 3: Longitudinal phase space at the end of the injector linac of all positrons with the optimised analytic SC solenoid matching device. The red box on the plot indicates the window of the PDR acceptance.

The field maps of different matching devices used in the simulation are compared and presented in Fig. 4, including the flux concentrator field, the realistic HTS solenoid and the optimised analytic SC solenoid field. The downstream fringe field of the matching device is replaced by a uniform magnetic field of 0.5 T, which is supposed to be provided by NC solenoids surrounding the RF structures. The position of the target exit face for the 380 GeV energy stage is also indicated on the plot.

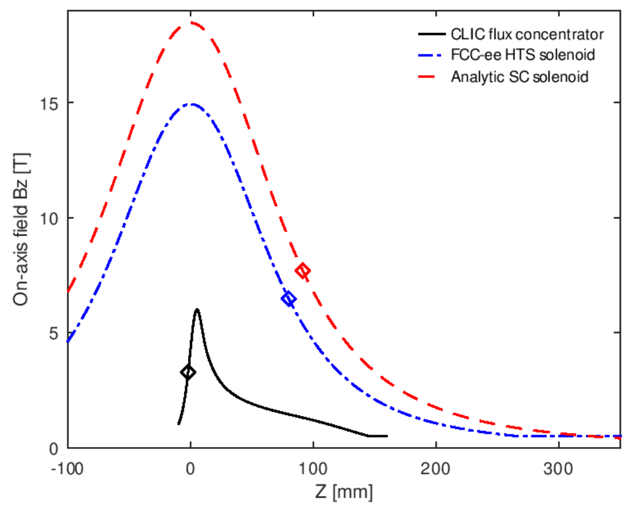

Figure 4: Comparison of field maps of different matching devices. The 'diamond' markers indicate the positions of the target exit face with regard to the peak fields.

CONCLUSION

With the development of SC solenoid technology, especially the HTS solenoid, it has become possible to use SC magnets as matching devices. Compared to conventional NC matching devices such as a quarter wave transformer (QWT) or a flux concentrator (FC), SC solenoids can provide a much higher peak magnetic field and improve the positron yield significantly. We tested the FCC-ee HTS matching device for the CLIC positron source and found an improvement of ~30% on the final positron yield compared with the flux concentrator. We also studied the analytic SC solenoid field, which gives highly consistent results with the realistic FCC-ee HTS solenoid, given the same coil parameters and peak field. An optimisation of the analytic SC solenoid with reasonable constraints gives ~3% more improvement on the positron yield.

ACKNOWLEDGEMENTS

We thank B. Auchmann, M. Duda, and J. Kosse, et al. from PSI for providing the HTS solenoid field map designed for the matching device of the FCC-ee positron source. We also thank H. Bajas for his efforts in designing the flux concentrator for the CLIC positron source when he worked at CERN.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL096

REFERENCES

[1] M. Aicheler *et al.*, "A Multi-TeV Linear Collider Based on CLIC Technology: CLIC Conceptual Design Report", CERN-2012-007 (2012). doi:10.5170/CERN-2012-007

[2] CLIC Accelerator Collaboration, "The Compact Linear Collider (CLIC) - Project Implementation Plan", edited by M. Aicheler *et al.*, CERN-2018-010-M (2018). doi:10.23731/CYRM-2018-004

[3] Y. Zhao *et al.*, "Optimisation of the CLIC Positron Source", in *Proc. IPAC'21*, Campinas, SP, Brazil, May 2021, pp. 2613–2616. doi:10.18429/JACoW-IPAC2021-WEPAB014

[4] S. Agostinelli *et al.*, "Geant4: A Simulation toolkit", *Nucl. Instrum. Meth.*, Vol. A506, pp. 250–303, 2003. https://doi.org/10.1016/S0168-9002(03)01368-8

[5] A. Latina, "RF-Track Reference Manual (2.0.4)", *Zenodo*, 2020. https://doi.org/10.5281/zenodo.3887085

[6] A. Abada *et al.*, "FCC-ee: The Lepton Collider", Eur. Phys. J. Spec. Top. 228, 261–623 (2019). https://doi.org/10.1140/epjst/e2019-900045-4

[7] I. Chaikovska *et al.*, "Positron source for FCC-ee", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. MOPMP003. doi:10.18429/JACoW-IPAC2019-MOPMP003

[8] Y. Zhao *et al.*, "Comparison of Different Matching Device Field Profiles for the FCC-ee Positron Source", in *Proc. IPAC'21*, Campinas, SP, Brazil, May 2021, pp. 2617–2620. doi:10.18429/JACoW-IPAC2021-WEPAB015

[9] Y. Zhao *et al.*, "Optimisation of the FCC-ee Positron Source using a HTS solenoid matching device", in *Proc. IPAC'22*, Bangkok, Thailand, June 2022, pp. 2003–2006. doi:10.18429/JACoW-IPAC2022-WEPOPT062

[10] B. Humann *et al.*, "Radiation load studies for the FCC-ee positron source with a superconducting matching device", in *Proc. IPAC'22*, Bangkok, Thailand, June 2022, pp. 2879–2882. doi:10.18429/JACoW-IPAC2022-THPOTK048

[11] J.C. Sheppard, "Conventional Positron target for a Tesla formatted beam", SLAC-TN-03-072 (2003). https://doi.org/10.2172/826573

[12] H. Bajas *et al.*, "Flux Concentrator Optimization for Future Positron Sources", in *IEEE Transactions on Applied Superconductivity*, Vol. 32, No. 6, pp. 1–5, Sept. 2022, Art. no. 0601105, https://doi.org/10.1109/TASC.2022.3160405

[13] M. N. Wilson, "Superconducting Magnets", *Monographs on cryogenics Oxford science publications*, Vol. 2, pp. 20–26. Clarendon Press, 1983.

[14] J. A. Nelder and R. Mead, "A Simplex Method for Function Minimization", *The Computer Journal*, Vol. 7, Iss. 4, pp. 308–313, 1965. https://doi.org/10.1093/comjnl/7.4.308

[15] J. W. Eaton *et al.*, "GNU Octave version 4.2.0 manual: a high-level interactive language for numerical computations", 2016. http://www.gnu.org/software/octave/doc/interpreter/