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OPTIMISATION OF THE FCC-ee POSITRON SOURCE USING A HTS SOLENOID MATCHING DEVICE

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Abstract

In this paper, we present the simulation and optimisation of the FCC-ee positron source, where a high-temperature superconducting (HTS) solenoid is used as the matching device to collect positrons from the target. The ”conventional” target scheme is used which simply consists of amorphous tungsten. The target is placed inside the bore of the HTS solenoid to improve the accepted positron yield at the entrance of the damping ring and the location of the target is optimised. The latest recommended baseline beam parameters are used and presented. An optimisation of the ideal positron yield using the analytic SC solenoid on-axis field is also performed and shows that the design of the HTS solenoid is optimal as far as the accepted positron yield is concerned.

INTRODUCTION

The matching device plays an important role in the FCC-ee positron source [1]. Positrons from the target are captured by the matching device with a strong magnetic field, followed by a capture linac that accelerates the positrons up to 200 MeV. The positrons are then accelerated by the injector linac to 1.54 GeV and matched to the damping ring (DR) acceptance at the DR entrance. The ratio between the number of positrons accepted by the DR and the number of primary electrons impinging on the target is defined as the ”accepted” positron yield.

In our study, the FCC-ee positron source is simulated from the target to the injector linac. The ”conventional” target scheme is assumed, which comprises a single amorphous tungsten target. Downstream of the target is the matching device. To increase the magnetic field at the target exit and improve the capture efficiency, a high-temperature superconducting (HTS) solenoid is used as the matching device, and the target is placed inside the bore of the HTS solenoid. The capture linac is composed of travelling wave (TW) or standing wave (SW) RF structures, surrounded by a normal conducting (NC) or superconducting (SC) solenoid that is assumed to provide a constant magnetic field. The injector linac is longitudinally simulated with an analytic calculation of the positron energy, while the transverse tracking is not considered. GEANT4 [2] is used to simulate the interactions between the primary electrons and the target. The target thickness is $5\,X_0$ (17.5 mm) [3], $X_0 = 3.5$ mm being the radiation length of the tungsten. Sampling with a Gaussian function is used to generate the initial distribution of electrons at the target entrance. RF-TRACK [4] is used to simulate the beam tracking in the matching device and capture linac. The schematic layout of the FCC-ee positron source assumed in this study is presented in Fig. 1.

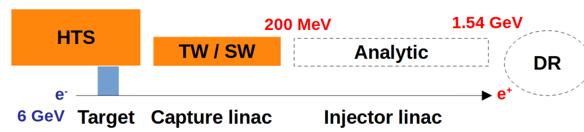

Figure 1: Schematic layout of FCC-ee positron source using the HTS solenoid as the matching device.

The latest recommended baseline primary electron beam parameters and positron beam parameters at the DR entrance, as well as the target parameters and energy depositions, are summarised in Table 1. The peak energy deposition density (PEDD) [1] and deposited power in the target are also presented, which are usually normalised by the accepted yield to achieve the required bunch charge at the DR entrance. A conservative normalised transverse emittance (~60 mm·mrad) is considered for the primary electrons. A smaller normalised transverse emittance (~15 mm·mrad) is also studied while the spot size is still the same (0.5 mm), and it is found that the impact on the results is negligible.

HTS SOLENOID

The HTS solenoid for the FCC-ee positron source is being designed and developed at the Paul Scherrer Institute (PSI) and the field map of the latest design [5] is used in our simulations. The solenoid is ~30 cm long including different parts such as the HTS coils, the radiation shield, the cryostat, etc. The outer diameter of the solenoid is assumed to be 46.5 cm, while the warm bore diameter is assumed to be 72 mm. Shielding material is assumed to be placed inside the warm bore surrounding the beam, with a thickness of 16–21 mm. Larger thickness of the shielding material than 21 mm would lead to more lost positrons and therefore reduce the accepted positron yield significantly.

The on-axis magnetic field of the HTS solenoid is displayed in Fig 2. The distance between the peak field and the solenoid exit position is designed to be ~100 mm. The full HTS solenoid field is presented by the dashed curve, while the effective field of the HTS solenoid that is used in the simulation is presented by the solid curve. In addition, a

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[1] Normalised PEDD is usually required to be < 35 J/g [6]

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Table 1: Beam and Target Parameters. Accepted Positron Yield Is Denoted as η_{e^+}

Parameters	Values	Units
Primary electrons at the target entrance		
Beam energy	6	GeV
Spot size (RMS)	0.5	mm
Bunch length (RMS)	1	mm
Energy spread (RMS)	0.1	%
Normalised transverse emittance (RMS)	~60	mm·mrad
Number of bunches per pulse	2	
Repetition rate	200	Hz
Normalised beam power	$16.8 / \eta_{e^+}$	kW
Normalised beam fluence	$6.2 \times 10^{11} / \eta_{e^+}$	cm^{-2}
Positrons at the DR entrance		
Bunch charge required	7	nC
Energy window cut	1540 ± 58.5	MeV
Time window cut (total)	~9.3	mm/c
Target ("conventional" scheme)		
Thickness	17.5	mm
Positron yield at target exit	13.7	e^+/e^-
Normalised PEDD	$26.2 / \eta_{e^+}$	J/g
Normalised deposited power	$4.1 / \eta_{e^+}$	kW

small part of the constant NC solenoid field that is used for the capture linac is also displayed as an example and presented by the red solid curve. The effective HTS solenoid field used in the simulation starts from the target exit which in this case is $z = 41$ mm and ends at where the constant solenoid field is started, which in this case is 0.5 T.

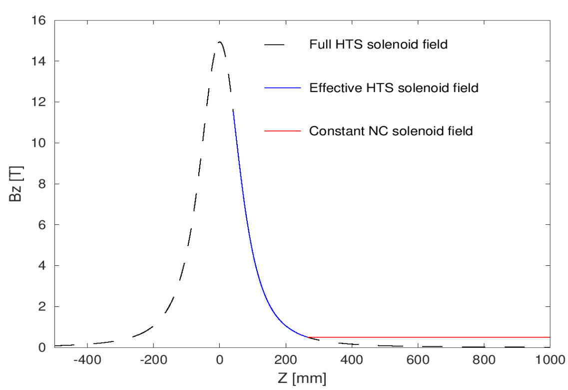

Figure 2: On-axis field of the HTS solenoid. A small part of the constant NC solenoid field is also displayed.

CAPTURE LINAC

The capture linac is supposed to accelerate the positrons captured by the matching device to around 200 MeV. To improve the capture efficiency as well as the accepted positron yield, the first RF structure of the capture linac is always working in decelerating mode. Two different RF structure profiles are studied for the capture linac:

- A 2 GHz L-band TW structure same as the one used in the CLIC pre-injector linac [7], working in the $2\pi/3$ mode with a 0.5 T constant NC solenoid magnetic field. The number of structures used is 11. The structure is designed to have a tapered inner aperture with the diameter decreased from 40 mm to 28 mm. However, a constant aperture is technically possible and a constant aperture of 40 mm diameter is applied in the simulation with the same field map. The structure is 1.5 m long, composed of 30 cells. The distance between the structures is 20 cm. The average gradient is 17.5 MV/m for the first decelerating structure and 21 MV/m for the other accelerating structures.
- A 3 GHz S-band SW structure that is being designed at PSI, working with a 1.5 T constant SC solenoid magnetic field. The number of structures used is 13. The inner aperture diameter of the structure is constantly 40 mm. The structure is 1.2 m long, composed of 21 cells. The distance between the structures is 15 cm. The average gradient is fixed at 18 MV/m for all structures with a 15 MW input power.

INJECTOR LINAC

The acceleration of positrons in the injector linac up to 1.54 GeV was calculated with an analytic formula: $\Delta E = \Delta E_0 \cdot \cos(2\pi f \cdot \Delta t)$. In the formula, $\Delta E_0 = 1.54\,\text{GeV} - E_{\text{ref}}$ is the maximum energy gain for the reference particle, $f = 2.856$ GHz is the frequency assumed for S-band injector linac RF structures and $\Delta t = t - t_{\text{ref}}$ is the time difference from the reference particle. The reference particle with an energy around 200 MeV was defined such that the mean energy of positrons accepted by the DR was exactly 1.54 GeV and the accepted positron yield was maximised.

The DR acceptance was considered by applying a window cut on the energy and time of positrons arriving at the injector linac exit or DR entrance. The accepted energy is within $\pm 3.8\%$ of the desired energy, 1.54 GeV, while the total size of time window is 9.33 mm/c corresponding to a conservative RF phase window of 32° at 2.856 GHz. The time window needs to be adjusted to the longitudinal acceptance of the DR, which will likely lead to a larger time window and therefore increase the accepted positron yield. The longitudinal phase space of the positrons at the end of the injector linac for the L-band TW structures capture linac profile is presented in Fig. 3, with the energy and time window displayed by a red dashed rectangle on the plot. The number of simulated primary electrons is 10,000. The overflow and underflow of positrons beyond the plotting ranges are also displayed in the statistics box of the plot. To simplify the window cut optimisation, the middle of the time window is always assumed to be the same with the time of the reference particle, which is set to 0 on the plot.

TARGET POSITION OPTIMISATION

The scan of the accepted positron yield as a function of the target exit position inside the bore of the HTS solenoid is presented in Fig. 4. The scan is simplified such that the step of scan is increased where the yield is found to be much lower than the maximum value. The maximum accepted positron yield is achieved at $z = +41$ mm (yield: $4.8\,e^+/e^-$) and $z = +20$ mm (yield: $6.0\,e^+/e^-$) for the L-band and S-

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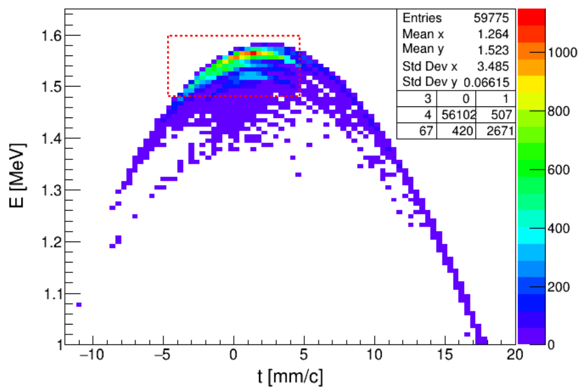

Figure 3: Longitudinal phase space of the positrons at the end of the injector linac for the L-band TW structures capture linac profile. Energy and time cut window are displayed by a red dashed rectangle on the plot. The time of the reference particle is set to 0.

band capture linac profiles respectively, with z being the target exit position inside the bore of the HTS solenoid and $z = 0$ being the peak field position of the HTS solenoid.

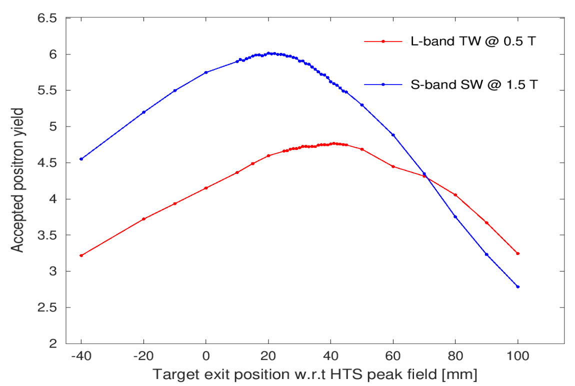

Figure 4: Scan of Accepted Positron Yield as a Function of the Target Exit Position

A comparison of the accepted positron yield between an 8 mm diameter entrance aperture flux concentrator (FC) [3] and a HTS solenoid as the matching devices is summarised in Table 2.

Table 2: Comparison of Accepted Positron Yields for Different Matching Devices and Different Capture Linacs

Yield comparison	**FC**	**HTS solenoid**
L-band RF @ 0.5 T	3.1 e^+/e^-	4.8 e^+/e^-
S-band RF @ 1.5 T	4.0 e^+/e^-	6.0 e^+/e^-

IDEAL SC SOLENOID AND YIELD

To verify if the designed yield, namely the accepted positron yield obtained with the designed HTS solenoid field, is optimal, an ideal yield is also estimated and optimised and compared with the designed yield. For the estimation of the ideal yield, a simple circular cylindrical SC solenoid winding of rectangular cross-section is used as the matching device, and the on-axis magnetic field is analytically expressed by the following formulae [8]:

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

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

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

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

Given similar parameters to those used in the designed HTS solenoid and the same target position, the ideal yield is found to be comparable with the designed yield, with a small difference of ~2% for instance for the L-band capture linac profile. Futhermore, the ideal yield is optimised with loose constraints on the solenoid parameters, for the L-band capture linac profile, as an example. As a result, the optimal ideal yield is found to be 5.1 e^+/e^- , which is not much higher (~6%) than the designed yield. In this case, the optimised target exit position is $z = +195$ mm, with $z = 0$ being the peak field position. The optimised ideal SC solenoid parameters, though it might be technically challenging and enpensive, are summarised in Table 3.

Table 3: Optimised Ideal Solenoid Parameters with loose constraints and Accepted Positron Yield for the L-band Capture Linac Profile.

J [A/mm^2]	**a [mm]**	**b [mm]**	**l [mm]**	**Ideal yield [e^+/e^-]**
890	60	90	196	5.1

Therefore the HTS solenoid design is thought to be optimal or very close to optimal in terms of the accepted positron yield.

SUMMARY

In this paper, we presented the simulation and optimisation of the FCC-ee positron source using a HTS solenoid as the matching device. The ”conventional” tungsten target is used and placed inside the HTS solenoid bore and the location of the target is optimised to improve the accepted positron yield at the DR entrance. The latest recommended baseline beam parameters are used and presented. The accepted positron yield using the HTS solenoid as matching device is significantly improved compared with using the flux concentrator. Ideal accepted positron yield is also estimated using analytic SC solenoid on-axis field and is found to be comparable with the designed HTS solenoid. An optimisation of the ideal accepted positron yield shows that the design HTS solenoid is optimal as far as the accepted positron yield is concerned.

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