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COMPARISON OF DIFFERENT MATCHING DEVICE FIELD PROFILES FOR THE FCC-ee POSITRON SOURCE

Y. Zhao*[1], L. Ma, Shandong University, Jinan, China
P. Martyshkin, BINP, Novosibirsk, Russia
S. Doebert, A. Latina, CERN, Geneva, Switzerland
I. Chaikovska, R. Chehab, IJCLab, Orsay, France
B. Auchmann, P. Craievich, J. Kosse, R. Zennaro, PSI, Villigen, Switzerland
[1]also at CERN, Geneva, Switzerland

Abstract

In this report, we compared different matching device field profiles for the FCC-ee positron source. The matching device is used to capture positrons with magnetic field. A flux concentrator was designed with a conical inner chamber. A smaller aperture and a larger aperture were studied. An analytic field profile was also studied using an adiabatic formula. The peak field of the analytic profile as well as beam and target parameters was optimised to achieve a maximum positron yield. A safe energy deposition in the target was guaranteed by requiring a constraint on the deposited power and peak energy deposition density.

INTRODUCTION

The FCC-ee positron source [1] is used to produce high energy positrons, which are then injected to the damping ring (DR). Positrons are supposed to be generated by high energy electrons impinging on a tungsten-rhenium (W_{75}-Re_{25}) alloy target. For simplification a tungsten target was simulated in this study. A matching device (MD) is placed very close to the target to capture positrons. Positrons are further captured and accelerated to 200 MeV by the pre-injector linac composed of travelling wave (TW) or standing wave (SW) RF structures and a surrounding normal conducting (NC) solenoid. Finally the injector linac will accelerate positrons to 1.54 GeV.

Positron yield is defined as the ratio of the number of positrons accepted by the DR to the number of impinged primary electrons. The peak energy deposition density (PEDD) in the tungsten target is required to be less than 35 J/g [2] for safety reasons. Positron yield and PEDD were optimised with a simple and efficient optimisation algorithm [3] based on iterations of scan of free parameters.

GEANT4 [4] was used to simulate the generation of the primary electron beam and the target. In case of using crystal tungsten target, FOT [5] was used to simulate the channelling process for the electrons. The phase spaces of the primary electrons were generated by a sampling with a gaussian function. RF-TRACK [6] was used to simulate the beam tracking in the MD and pre-injector linac. Three different field profiles were studied for the MD:

- A 3D field map from a flux concentrator (FC) simulation with a conical inner chamber. A high peak field was achieved with a smaller aperture.
- A similar FC but with a larger aperture and a lower peak field.
- An analytic adiabatic matching device (AMD) on-axis field profile assuming a constant large aperture.

The injector linac was actually not simulated, but simply considered with an analytic description.

The main parameters of the primary electron beam used in the study are summarised in Table 1. The spot size of primary electrons was optimised and found to be different for different MD field profiles. Therefore it is not included in the Table.

Table 1: Main Parameters of the Primary Electron Beam

Parameters	Values	Units
Beam energy	6	GeV
Energy spread (RMS)	0.1	%
Divergence (RMS)	0.01	mrad
Bunch length (RMS)	1	mm
Number of bunches per pulse	25	
Repetition rate	100	Hz

The positron bunch population was required to be 2.1×10^{10} (~3.4 nC bunch charge). An additional safety factor of 2 was considered.

TARGET

At present, two target schemes have been studied for the FCC-ee positron source:

- A hybrid target scheme, composed of a thin crystal tungsten target and a thick amorphous tungsten target with a long distance between the targets. A dipole with strong magnetic field was used to deflect and remove charged particles between the targets, leaving only photons to impinge on the amorphous target, such as to reduce energy deposition in target.
- A conventional target scheme, composed of a single amorphous tungsten target.

An optimisation of positron yield for the hybrid target scheme shows that the accepted positron yield was reduced significantly by the long distance between the crystal and amorphous targets, as shown in Fig. 1. The positron yield was expected to be maximum when the distance is zero.

* yongke.zhao@cern.ch

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The decrease of yield is actually due to that on one hand the long distance increased the beam size of photons and positrons, and on the other hand the charged particles (mainly remaining electrons taking ~40% of primary beam power) removed by the dipole could also contribute to the positron production.

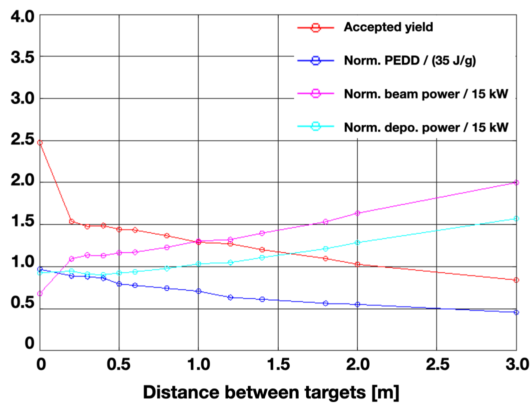

Figure 1: Scan of the distance between the two targets.

Nevertheless, the study of hybrid target scheme is still in progress as it is thought to have potential advantages of reduced PEDD and thermal load in the target. Therefore in this study the conventional target scheme was adopted. The thickness of the conventional target has been optimised to achieve a maximum positron yield and meanwhile a deposited power in the target that was as small as possible. The optimised value is $5\,X_0$ (17.5 mm), $X_0 = 3.5$ mm being radiation length of the tungsten.

MATCHING DEVICE

For the FC scheme, a pulsed FC with a conical inner chamber was designed [7] for the FCC-ee positron source. The sketch of the FC is presented in Fig. 2. A NC solenoid was used to provide a constant magnetic field that is the same for all capture sections.

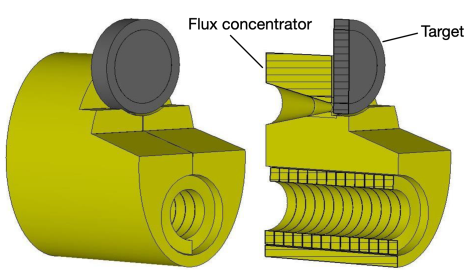

Figure 2: Sketch of the FC.

For such a FC, typically a higher peak field can be achieved by using a smaller aperture, while alternatively a larger aperture can be used but with a lower peak field.

For the smaller aperture scheme, the peak field is 7 T. The aperture diameter is increased from 8 mm to 44 mm. The total length of the FC is 140 mm, with the conical part 70 mm long. The distance between the target and the FC is 2 mm.

For the larger aperture scheme, the peak field is 5 T. The aperture diameter is increased from 16 mm to 63 mm. The total length of the FC is 200 mm with the conical part 100 mm long. The distance between the target and the FC is 5 mm.

For the analytic AMD profile, an adiabatic formula [8] was used to describe the ideal on-axis magnetic field:

$$B_z = B_0/(1 + \mu z)\,, \tag{1}$$

where z is the longitudinal coordinate with $z = 0$ at the downstream surface of the target, B_0 is the peak field at $z = 0$ which was optimised to be 12 T in our study, B_z is the on-axis magnetic field decaying from B_0 to 0.5 T, μ determines the decay rate of the magnetic field along z which was set to be constantly 50 m^{-1} in our study.

In the positron tracking simulation, a constant aperture of 20 mm radius was assumed. The optimisation of B_0 is presented in Fig. 3, where B_0 was scanned with optimised electron spot sizes. The optimisation also provides possibilities to use smaller B_0 values but with reduced positron yields. The optimised spot size is 1.0 mm for $B_0 \geq 7$ T and increased to 1.1-1.2 mm for $B_0 < 7$ T to reduce the PEDD. Improvement in positron yield with a smaller spot size below 1 mm is not obvious, but the increase in PEDD is significant.

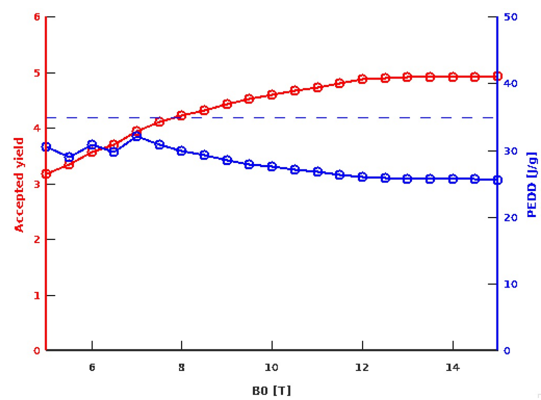

Figure 3: Scan of B_0 with spot size optimised.

A conceptual design of high-temperature superconducting (HTS) solenoid is being investigated at the Paul Scherrer Institute (PSI). The possibility of approximately realising the analytic field profile has been studied by placing a combination of coils both upstream and downstream of the amorphous target with the thermal and mechanical considerations neglected. The study is very promising given that the analytic field profile used as the objective function can be accurately reproduced. However, it was also found that the coil geometry and the magnetic field profile would be undoubtedly changed with the thermal and mechanical considerations included. And an iterative process is thought to be necessary between the realistic simulations and the thermo-mechanical magnetic designs.

The comparison of the three different AMD on-axis fields used in the study is presented in Fig. 4. In the plots, $z = 0$ corresponds to the target exit position.

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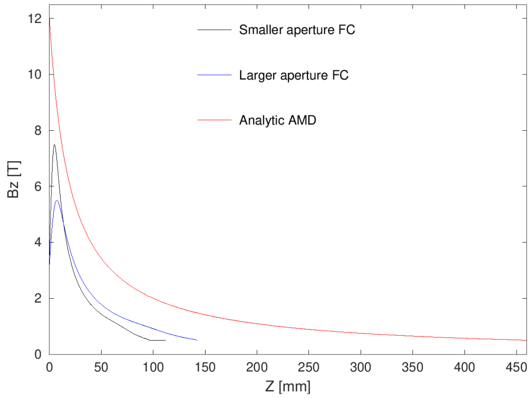

Figure 4: Comparison of different AMD on-axis fields. The target exit is at $z = 0$ mm.

PRE-INJECTOR LINAC

The same pre-injector linac with the CLIC [9, 10] positron source was used in this study. The pre-injector linac is composed of 11 L-band travelling wave (TW) structures working in the $2\pi/3$ mode with a frequency of 2 GHz and an aperture of 20 mm radius. Each TW structure is 1.5 m long, composed of 30 cells. The first structure was supposed to capture positrons with deceleration, while the others accelerate positrons to 200 MeV. The distance between the FC and the first TW structure is 40 mm. The distance between the structures is 20 cm. The TW structures are surrounded by a NC solenoid with a constant magnetic field of 0.5 T. The average gradient for the TW structures is 16 MV/m.

INJECTOR LINAC

The acceleration of positrons in the injector linac up to 1.54 GeV was simplified in the simulation with an analytic calculation: $\Delta E = \Delta E_0 \cdot \cos(2\pi f \cdot \Delta t)$. In the formula, $\Delta E_0 = 1.54\,\mathrm{GeV} - E_{\mathrm{ref}}$ is the maximum energy gain for the reference particle, $f = 2.856$ GHz is the RF frequency assumed for S-band structures and $\Delta t = t - t_{\mathrm{ref}}$ 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 acceptance of DR was considered by applying a window cut on the energy and time of positrons arriving at the injector linac exit. The energy acceptance 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 RF phase window of 32°. The longitudinal phase space of the positrons at the end of the injector linac for the analytic AMD profile is presented in Fig. 5, with the energy and time window displayed by a red rectangle on the plot.

RESULTS

The final simulation results, including the accepted positron yield, the PEDD and deposited power in the target and the primary electron beam power, are summarised in Table 2 for different MD field profiles. The PEDD, deposited power and primary beam power are all normalised to the required bunch charge and number of bunches by the accepted positron yield at the entrance of the DR. The optimised spot size of the primary electrons is presented as well.

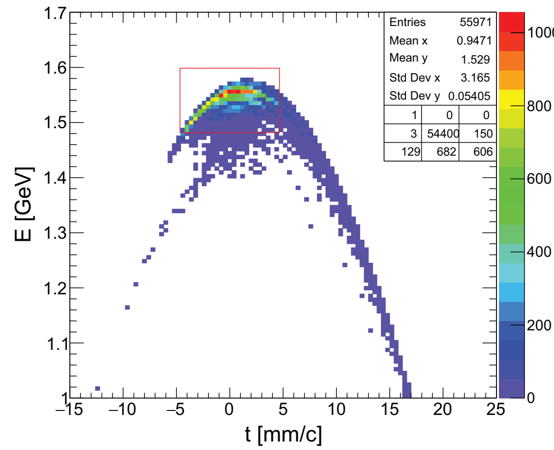

Figure 5: Longitudinal phase space of the positrons at the end of the injector linac for analytic AMD profile. Energy and time cut window are displayed by a red rectangle on the plot. The time of the reference particle is set to 0.

Table 2: Normalised Results for Different MD Field Profiles

Results	8 mm FC	16 mm FC	Analytic AMD	Units
Spot size	1.5	1.4	1.0	mm
Beam power	42.2	42.3	20.7	kW
Deposited power	10.2	10.2	5.03	kW
PEDD	29.7	31.9	26.0	J/g
Positron yield	2.39	2.38	4.88	

8 mm FC refers to the FC with a smaller aperture that the entrance aperture diameter is 8 mm. Similarly, 16 mm FC refers to the FC with a larger aperture.

SUMMARY

In this report, we compared three different matching device field profiles and simulated the tracking from the target to the entrance of the DR for the FCC-ee positron source. The conventional target scheme with a single amorphous tungsten target was adopted in the simulation. Positron source parameters were briefly optimised to achieve the maximum positron yield. Final normalised simulation results as well as optimised primary electron spot sizes are given for different matching device field profiles. A larger aperture of the FC with a lower peak field was found to achieve comparable positron yield with a smaller aperture. An analytic AMD simulation with a constant large aperture and an optimised peak field can achieve a much higher positron yield, which indicates a very promising improvement in positron yield by using a superconducting solenoid as the matching device.

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