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UPDATE OF THE CLIC POSITRON SOURCE

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Abstract

The positron source of the CLIC has been optimized several years ago for the 3 TeV and 500 GeV c.o.m.-energy stages, and in a recent reoptimization the positron transmission efficiency from the tungsten target to damping ring entrance has been improved by a factor 2.5. Now, since the first stage of CLIC has been proposed to be at 380 GeV, new alternatives to the baseline design have been considered with the aim of improving the machine performance and its overall power efficiency, while possibly reducing the cost. For example, reducing the initial electron beam energy from 5 GeV to 3 GeV. In this paper, we present a start-to-end simulation environment which was setup for the whole positron source optimization. For the very first time a whole simulation including the positron creation in the hybrid tungsten targets, the adiabatic matching device, the pre-injector and the injector linacs has been put in place. First result of the new setup was to confirm of the transmission efficiency of the new improved baseline. Secondly, an ongoing optimization is promising even better results.

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INTRODUCTION

As a linear collider, the positron source is an essential system for the CLIC. The sketch layout of the CLIC positron source is shown in Fig. 1. It can been seen that the positron source is composed by the primary electron gun and linac, the hybrid tungsten targets, the pre-injector linac and the injector linac. For a positron source having a high positron yield (defined as N_{e^+}/N_{e^-}) is very important, because a higher positron yield requires lower injected primary electron energy and lower primary electron current.
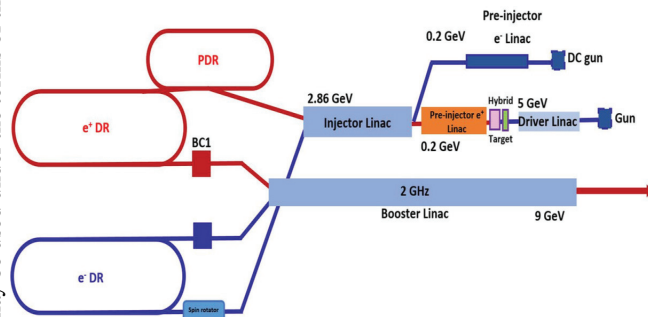

Figure 1: Sketch layout of the CLIC main beam injector complex. The positron source is at the top-right corner.

The baseline parameters for the hybrid tungsten targets in the CLIC CDR [1] are shown in Table 1. The positron yield

after the targets is 8.0 e^+/e^-. Here, the r.m.s. transverse spot size for the primary electron bunch is 2.5 mm and the electron energy is 5 GeV. The adiabatic matching device (AMD) is used to reduce the momentum divergence for the generated positrons. After the AMD, the positron yield is 2.1 e^+/e^-. Then the positron bunch is first decelerated and then accelerated in the pre-injector linac to 200 MeV. Then, the injector linac boosts the energy of the positrons to 2.86 GeV for injection int the damping rings. At the end of the injector linac, the effective positron yield is 0.39 e^+/e^- within the energy acceptance window of 1%.

Table 1: The parameters of the positron target

Crystal Thickness	Distance	Amorphous Thickness
1.4 mm	2 m	10 mm

In recent years a detailed optimization of the pre-injector linac was performed, starting from the AMD [2]. This study brought the positron yield from 0.39 to 0.97 e^+/e^-, using the same CDR targets parameters set. This was an important improvement that enabled a significant cost reduction: we could reduce the primary electron current, limit the peak energy deposition density (PEDD) in the tungsten target, and remove a whole secondary tungsten target that in the CDR was foreseen for coping with the material damage.

As the same time, the CLIC rebaselining process, aimed at optimizing the first stage of CLIC at 380 GeV in terms of performance, cost, and power efficiency [3], redefined the main beam parameters, increasing the single-bunch charge. The request for an increased positron current encouraged an overall optimization of the entire positron source in all its components. We therefore decided to perform a global optimization including: the primary electron bunch parameters, the hybrid targets, the AMD, the pre-injector and the injector linac.

THE PRIMARY ELECTRON BUNCH

The parameters of the primary electron bunch have a large effect on the PEDD, which is limited to 35 J/g. These parameters include the electron energy, the bunch length, the current and the transverse spot size. In our simulation, all those parameters can be scanned in order to get the best configuration.

HYBRID TARGETS

A hybrid-target scheme is adopted in CLIC in order to limit the PEDD in the amorphous tungsten target. The first target is a crystal tungsten. When the primary electrons impinge on this crystal, high energy photons are radiated through a channeling process. In order to simulate the channeling process, the software FOT [4] is used. At the time of the CDR, the simulation of the channeling process was simulated with another software, VMS [5]. There is a known 10% to 20% discrepancy between these two softwares, due to their different implementation logic. In our simulation, we opted for FOT because the VMS could not be found and in fact was dismissed years ago.

The radiated high-energy photons are then used as primary particles in GEANT4 [6]. The standard electromagnetic process in the crystal and amorphous tungsten is simulated by the GEANT4. Between the two targets, a 1 T dipole field is used to bend the electron-positron pairs generated in the crystal target, further reducing the PEDD. This field is simulated with GEANT4. Downstream of the amorphous targets only the positrons' information is saved for the following steps of the simulation.

ADIABATIC MATCHING DEVICE

An adiabatic matching device (AMD) is an adiabatically tapered solenoidal magnetic field and it is used to match the positron beam phase space to the following accelerating section. The on-axis magnetic field of an AMD can be expressed as

$$B(z) = \frac{B_0}{1 + \mu z}.$$

The off-axis field can be calculated starting from it using the Maxwell equations, as it was done in [7]. The AMD was implemented in the tracking code RF-Track [8]. For our simulation, the initial magnetic field B_0 is 6 T and $\mu = 55 \text{ m}^{-1}$. The length of the AMD was 20 cm. Figure 2 shows the positron energy and transverse divergence after the target and AMD, for a 5 GeV primary electron bunch and the CDR target parameters.

The positron yield after the targets is about 7.2, which is smaller than the 8.0 obtained with the VMS for channeling process. After the AMD, only the positrons with energy smaller than 20 MeV have large probability to survive. The transverse divergence gets squeezed thanks to the adiabatic process. The positron yield is about 2.6 after the AMD.

PRE-INJECTOR

The pre-injector is composed by 11 RF cavities embedded in a solenoid tube with magnetic field of 0.5 T. These are 2 GHz RF cavities, working in $2\pi/3$ traveling-wave mode. While the first cavity must work in decelerating mode in order to facilitate bunching, the others work in accelerating mode. The length of each cavity is 1.5 m and they are separated by a 20 cm distance.

The pre-injector was simulated with RF-Track, which requires full 3-D field maps of the electric and magnetic
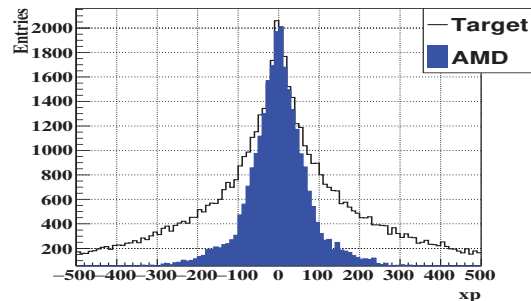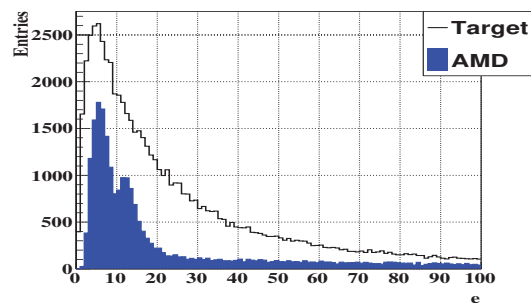
Figure 2: The energy and momentum divergence after the hybrid target and the AMD.

fields in the structures. The field maps were calculated with CST 2017 [9]. Tracking was performed using a 2nd-order Runge-Kutta with a step size of 3 mm. For the pure solenoid part, the step size is 4 mm. The aperture was 2 cm.

Since each RF cavity presents two degrees of freedom (the phase and the gradient), potentially there are 22 degrees of freedom in total for all the 11 RF cavities. In order to speed up the simulation, we used just 4 degrees of freedom: the phase and gradient for the first decelerating RF cavity, then the same phase and gradient for all the downstream accelerating cavities.

We used a Nelder-Mead algorithm (also known as simplex method) to maximize the positron yield, using these 4 degrees of freedom. The longitudinal phase space and the transverse divergence, after the first decelerating traveling structure are shown in Fig. 3.

Using an optimal decelerating phase and gradient, the high-energy positrons are largely decelerated, whilst the low-energy ones don't loose significant energy. This causes the bunching of the positrons. In Fig. 3, the bunching is visible around time 1850 mm/c (about 6.1 ns). The average energy for these positrons is about 10 MeV. The transverse divergence is smaller than that at the AMD exit.

In the downstream accelerating RF cavities of the preinjector-linac, the bunched positrons are captured and accelerated. The longitudinal phase space and the transverse divergence at the pre-injector end are shown in Fig. 4. The energy spread is very small and almost all positron are located around the centroid (< 20 mm/c). Almost all positron can be properly injected to damping rings. The positron yield after the pre-injector is 0.92 e^+/e^-, which is not signif-
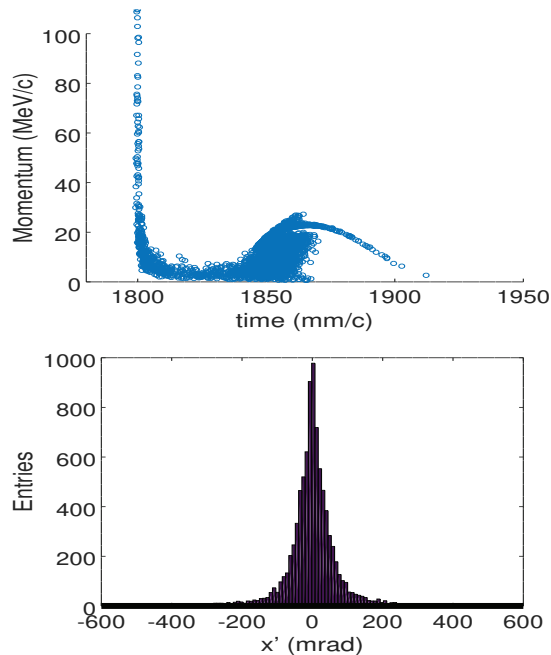
Figure 3: The longitudinal phase space and the transverse divergence after the decelerating RF cavity.

icantly different from the previous result 0.97 e^+/e^- in [2], where VMS was used for channeling process and PARMELA for tracking.
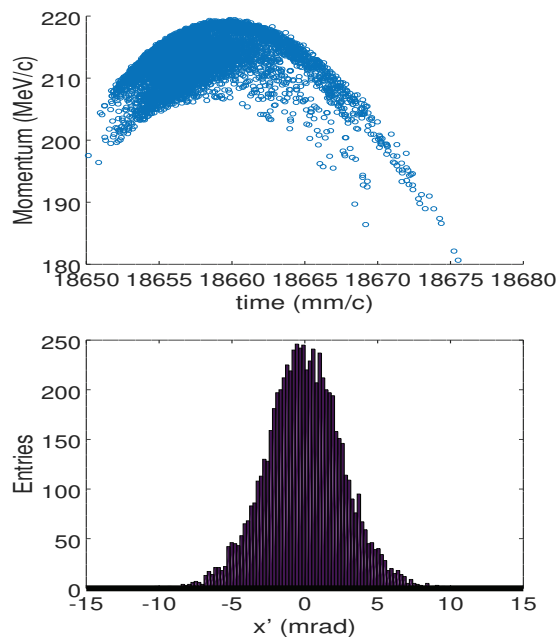

Figure 4: The longitudinal and transverse phase space at the pre-injector exit.

INJECTOR LINAC

The injector linac boost the positron energy from 200 MeV to 2.86 GeV. The linac design has been presented in [2]. The tracking for this injector linac can be performed with the tracking code PLACET [10]. Since no losses are expected in the injector linac, we just calculated the positron energy with the formula $E_f = E_i + \Delta E \cos(2\pi\omega t)$, here E_f and E_i denote the energy after and before the injector linac, ΔE is energy difference for the reference positron before and after the injector linac, ω is the frequency of the RF cavities, and t is the positron arrival time at the end of the pre-injector.

START-TO-END OPTIMIZATION

Two nested Nelder-Mead minimization algorithms were used to perform the start–to-end optimization. The first is the global optimization, which considers three free parameters: the thickness of the crystal tungsten target, the distance between the crystal and the amorphous tungsten target, and the thickness of the amorphous tungsten target. For each target parameter set, the software FOT and GEANT4 are called to simulate the channeling process and the electromagnetic process. Then RF-Track is called to simulate the AMD.

For the pre-injector and injector linac, the second stage optimization is performed. The second Nelder-Mead algorithm accepts then four free parameters: the phase and gradient for the decelerating and accelerating modes.

The merit function for the global optimization is the final positron yield. For each target configuration, we look for the highest positron yield and then calculate the PEDD. If the PEDD is smaller than the limit, i.e. 35 J/g, this positron yield is valid. Otherwise we reject the set of parameters. The merit function for the second stage optimization is the positron yield at the end of the injector linac. Additionally we require the final relative energy spread be smaller than 1.2% and within a time range of max 20 mm/c. The start-to-end optimization is a complex and time consuming simulation.

SUMMARY

We have setup a start-to-end optimization environment for the CLIC positron source. It includes the primary electron bunch, the two-stage hybrid tungsten target, the AMD, the pre-injector working on decelerating and accelerating modes, and the injector linac. This new simulation environment use the most appropriate tool for each specific task: FOT for channeling process, GEANT4 for the electromagnetic process, RF-Track for the detailed tracking in the AMD and in the cavities' field map, PLACET for the tracking relativistic linac, and the Nelder-Mead algorithm for the optimization. This new simulation environment has confirmed the results presented in [2], using the same target parameters outlined in the CLIC CDR. A more general start-to-end optimization including the impinging electrons parameters is on-going. We anticipate even better results both in terms of positron yield and compactness. The new baseline parameters will be based on the results of this optimization.

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