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Optimisation of the CLIC positron capture LINAC taking into account Beam Loading effects

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Abstract. This paper investigates Beam Loading in the positron source capture Linac of the Compact Linear Collider (CLIC). Beam Loading, caused by interactions between beam with accelerating cavities, leads to a reduction in the accelerating gradient, negatively affecting the Linac performance. Through simulations using the RF-Track code, we analyze Beam Loading effects and explore some optimization strategies. Key findings reveal significant transient Beam Loading effects and bunch-to-bunch variations.

1 Introduction

The Compact Linear Collider (CLIC) [1], is one of the most advanced projects proposed to achieve high-energy particle collisions at up to 3 TeV. Achieving high luminosity and optimal parameters at the interaction point (IP) is a common challenge for all lepton colliders, including CLIC, ILC [2], and SuperKEKB [3]. Due to the positron production nature, the positron source is a crucial component for capturing and accelerating positrons efficiently. Shown in Figure 1, positrons and electrons are produced in the target-converter by high-energy 5 GeV electrons. They are immediately focused using a special focusing magnet known as the Adiabatic Matching Device (AMD). Subsequently, positrons are captured and accelerated to 200 MeV by the pre-injector LINAC, referred to as capture LINAC. The structure encounters significant challenges from Beam Loading (BL) especially considering the large energy spread and bunch length of both electrons and positrons produced in the source. Beam Loading reduces the available accelerating gradient, thereby degrading the overall performance of the Linac. Finally, the Injector LINAC (IL) accelerates the positrons from 200 MeV to 2.86 GeV in preparation for the Damping Ring (DR).

Various optimizations are possible for the phase of the accelerating structure aiming to achieve minimum bunch length, energy spread, or maximum yield. This paper presents a study of overall optimization, including Beam Loading effect considerations.

2 RF Track and Beam Loading effect

Beam Loading occurs when particles crossing a cavity induce excited fields that reduce the cavity voltage and, consequently, the accelerating gradient. This effect persists over time and

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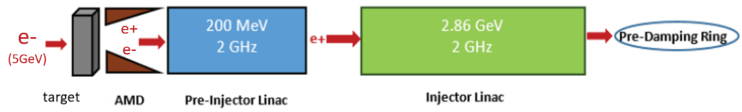

Figure 1. Positron source layout

accumulates from bunch to bunch. In the CLIC Capture Linac, both positrons and electrons contribute to Beam Loading, making it a particularly complex problem to address. Studying self-induced electromagnetic forces requires solving Maxwell's equations. This highly complex process, leading to the development of specialized computer codes like CST Studio Suite [4]. However, this approach is extremely time consuming especially for large lattices. Alternatively some tracking codes, like PLACET [5], use self-consistent wakefield calculations based on the single-cell damped-oscillator model which is relatively simplistic but does not account for the effects of cavity coupling crucial for Traveling-Wave (TW) structures. This has been achieved using a power-diffusive model similar to the model presented in [6]. A dedicated Beam Loading module based on this model has been implemented in a new fast-tracking code, RF-Track [7], recently developed at CERN. It allows tracking under the influence of both external and self-induced forces, capable of using complex 3D field maps and computing self-consistent single-particle and collective effects like space-charge, ensuring a comprehensive analysis of beam dynamics. The Beam Loading effect has also been implemented as a collective effect. Using the finite-difference method [8], a two-dimensional space-time mesh calculates the Beam Loading effect at each tracking step computing the gradient of the electromagnetic field by solving power diffusive equation derived from the Poynting theorem at the particles' positions and times in each step through cubic interpolation [9].

3 Simulation and Results

3.1 Electron and positron simulation without Beam Loading effect

The nominal 3 TeV CLIC beam consists of a bunch train with 312 bunches, each spaced 0.5 ns apart, and carrying $3.7 * 10^9$ positrons [1]. Figure 2 illustrates the initial longitudinal phase space distribution of electrons and positrons for each bunch at the Capture Linac entrance. (see Figure 1). The top-right plot provides an overview of the bunch in both time and energy, illustrating a broad energy spread extending up to 5 GeV (the energy of the electron impinging on the target). The Positron Capture Linac (Figure 3) consists of structures with a $2\pi/3$ traveling wave configuration, operating at a frequency of 2 GHz. Each structure includes 30 cells with a 20 mm aperture. Key parameters are summarized in Table 1.

Various optimizations can be applied when configuring the phases of the accelerating structures (Section 3.3) resulting in different final energy, loss percentage, and beam dynamics evolution along the structures. It has been shown that initial deceleration can significantly enhance capture efficiency [10]. To investigate Beam Loading effects, we utilized a configuration of 11 structures: initial on-crest bunch deceleration followed by on-crest acceleration in the remaining structures. Figure 4 depicts the longitudinal phase space at the end of the Capture LINAC for both species without Beam Loading consideration. Upon entering the first structure, both species encounter an identical phase of the electric field. However, due

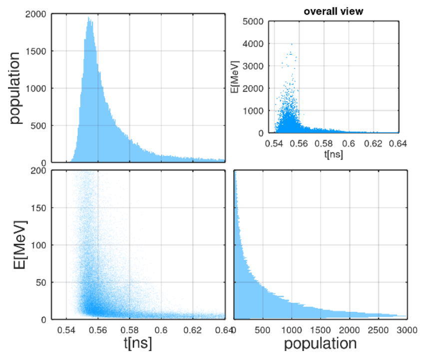

Figure 2. Initial distribution (longitudinal phase-space) for positron and electron at the output of AMD,The bottom-left plot magnifies the top-right plot and the other two are the population projections over time and energy

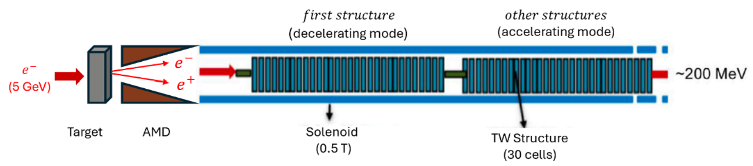

Figure 3. Capture Linac layout

Table 1. TW structure parameter

Parameter	Value	Unit
frequency	2	GHz
Q-factor	18346	
Input power	59.54	MW
Structure length	1.5	m
Average group velocity	1.45	% c
Filling time	345	ns

to the optimization of the field phase for positron acceleration, electrons experience deceleration and consequent energy loss. This causes electrons to gradually deviate by half an RF wavelength compared to positrons, ultimately settling on the crest of the electric field for acceleration (right Figure 4). Consequently, both particle species extract energy out of the structure. It should be noted that in this phase arrangement, we reach the goal of 200 MeV with 8 structure and a yield of 1.67.

Upon observing various RF wavelengths in longitudinal phase space Figure 4 in overall view of phase space in time, due to the significant energy spread, one will notice electrons being captured in multiple distinct RF buckets. Optimizing the phase for positrons, however, enables them to be better captured. In addition, without considering the Beam Loading effect, there is no difference between the bunches, and the phase space is identical for all bunches in the train.

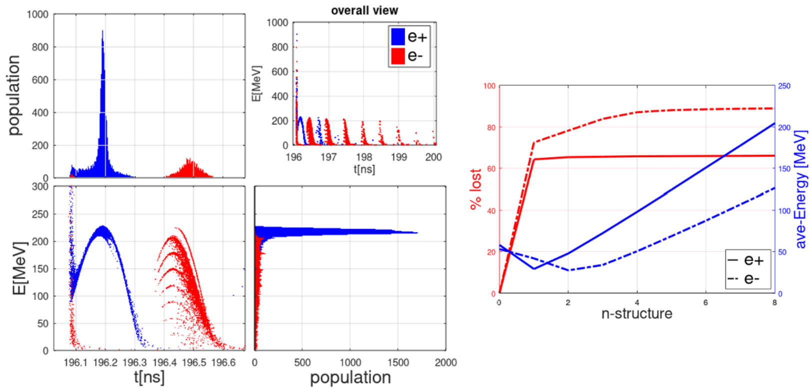

Figure 4. left : Longitudinal phase-space for electrons (red) and positrons (blue) without Beam Loading consideration. right: Average energy and loss percentage

3.2 Positron simulation with Beam Loading effect consideration

Each bunch entering the structure generates transient fields inside the cavity. These fields lead to a decrease in the gradient along the structure, known as Beam Loading effect. Figure 5 illustrates this gradient for a positron beam consisting of 312 bunches with bunch charge of 1.20 nC injected into the structure at an injection frequency of 2.0 GHz. The solid blue line represents the unloaded gradient. As the beam enters the structure, indicated by the red-dashed lines, a time dependent reduction in gradient occurs.

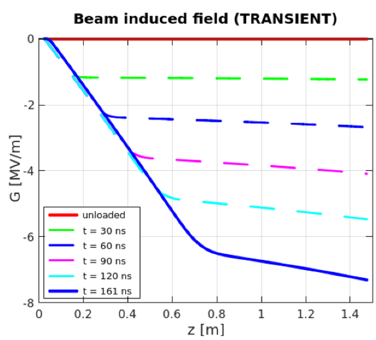

Figure 5. Illustration of the gradient reduction in the structure due to the beam loading effect of the positrons interacting with the cavity.

Incorporating the Beam Loading effect into the field map, we observe significant dynamics within the bunch train. The structure's filling time of 345 ns, coupled with a train comprising 312 bunches separated by 0.5 ns (2 GHz bunching frequency), prevents Beam Loading from reaching a steady state. Consequently, each bunch encounters a distinct Beam Loading effect. In Figure 6, we present the longitudinal phase space of positrons for the first ($N_b = 1$), middle ($N_b = 150$), and one of the last bunches ($N_b = 300$).

Variations are noted in other parameters across different bunches, including loss percentage (about 1%) and final energy (a significant amount about 23% at 200 MeV) along the

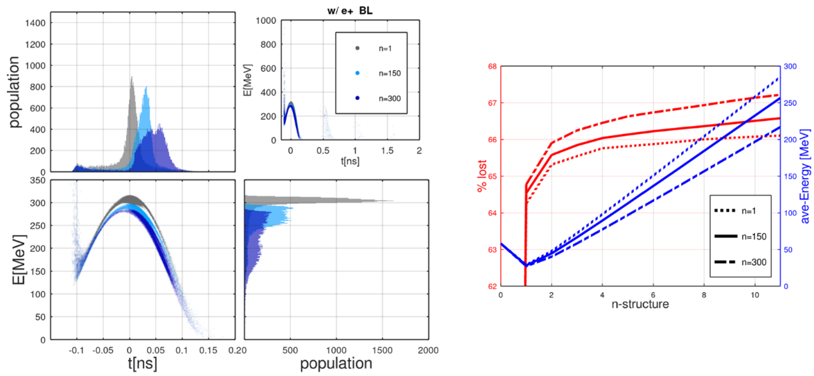

Figure 6. left: Longitudinal phase-space right: Average energy and loss percentage for positrons considering positron Beam Loading. Results are shown for the first, middle, and one of last bunches in the train, (the deceleration phase applied in the first structure and acceleration phases in the subsequent structures.)

structures of the capture LINAC (right plot of Figure 6). Variations in current and energy must be taken into account for Damping Ring acceptance consideration. These will affect the final yield and potentially impacting final luminosity. The energy acceptance of the damping ring is ±1%, and the bunch-to-bunch charge stability requirement for the collider is 0.1%. Therefore, it is crucial to consider the number of positrons and the resulting yield variation across the bunches in a train.

These findings underscore the complex interplay between beam dynamics and field effects, emphasizing the need for thorough consideration in accelerator design, optimization and operation.

3.3 Phase optimization of the accelerating structures

It has been shown that initial deceleration can significantly enhance capture efficiency [10]. Therefore carefully adjusting the RF phases of the first few structures is crucial to improve yield and efficiency. The phase scan of the first structure, shown in Figure 7, indicates a broad range with minimal loss. Various optimizations are possible for the phase of the structure aiming to achieve minimum bunch length, energy gain, energy spread, or minimum loss for first structure.

To achieve the required high-intensity positron beam needed for high Luminosity CLIC, it is critical to maximize the positron yield, defined as the number of positrons divided by the number of electron impinging on the target (N_{e+} / N_{e-}). Optimizing this yield is essential for meeting the beam intensity requirements. The CLIC CDR [11] reports a yield of 0.39 for the baseline hybrid tungsten design. Subsequent optimizations have achieved yields of 0.97 [12], and 0.92 with a revised single-target design [13]. A recent optimization study on the capture LINAC achieved a yield of 2.2 using 11 structures [14]. The phases of the first two structures have been optimized to maximize yield. Longitudinal phase space for the last bunch in this optimization is shown in Figure 8 considering Beam Loading effects. It can be seen that in this phase optimization, positron Beam Loading affect the bunch length energy spread and final energy along the bunch train. The variation in loss percentage along the bunch train is less than 1%, while the energy gain varies approximately 18% within the train.

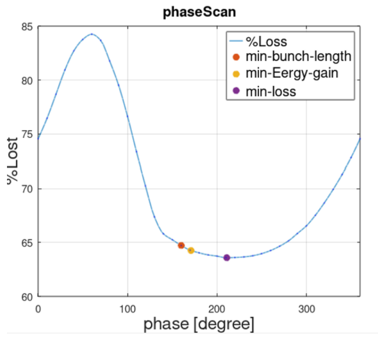

Figure 7. Phase-scan of the first accelerating structure

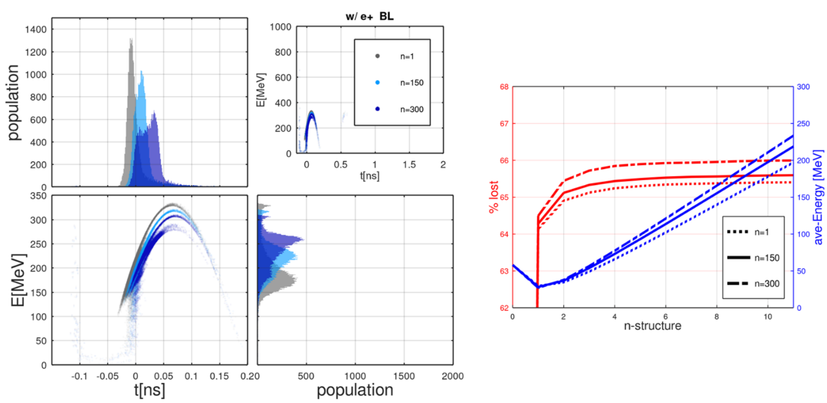

Figure 8. left: Longitudinal phase-space right: Average energy and loss percentage for positrons considering positron Beam Loading. Results are shown for the first, middle, and one of the last bunches in the train, (optimized phases obtained in [14].)

In our study, we further optimized the capture LINAC by adjusting the phases to their optimum to maximize the yield into the damping ring, enhance acceleration efficiency, and reduce energy spread. This optimization resulted in a 200 MeV output using 8 structures, with less energy spread and an almost identical yield of 2.2. Left Figure 9 illustrates the phase space of the new phase tracking. Considering Beam Loading (right, Figure 9) a comparison with Figure 8 demonstrates that in the optimized phase, variation among bunches is reduced (less than 0.5 % in loss and about 5 % in final Energy at 200 MeV), and sensitivity of bunch length to Beam Loading is decreased. Consequently, this phase configuration could prove to be more robust for further acceleration in the following Injector LINAC. Results have been summarized in 2. Furthermore, compared to Figure 4, this phase configuration results into a greater energy difference between the positron and the electron bunches. As a consequence, bunches of different species can be more efficiently separated after this step.

4 Conclusion and Future Work

This study presents the results of Beam Loading simulations in the CLIC positron source capture Linac using RF-Track version 2.2. Positron Beam Loading effect were quantified,

Table 2. Results for 200 MeV bunches

phase configuration	dec-acc	optimization[14]	New-optimization
Number of Structures	8	11	8
Yield	1.67	2.23	2.21
Energy of 300$^{\text{th}}$ bunch [MeV] (considering BL effect)	153.45	233.34	188.61
Maximum % of energy deviation	23.27	18.47	5.69
Maximum loss deviation	about 1 %	less than 1 %	less than 0.5 %

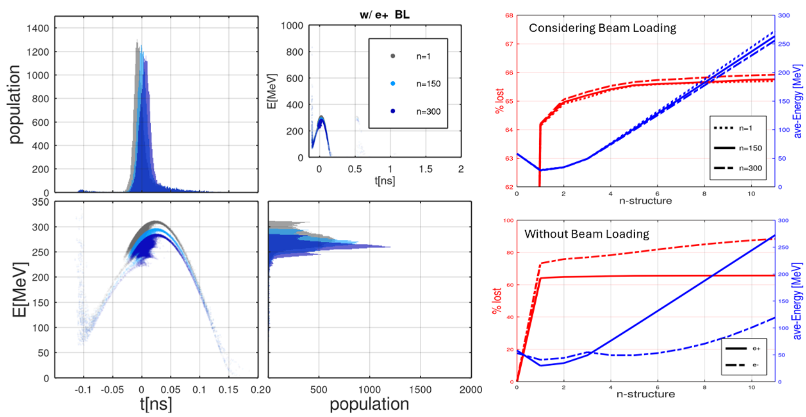

Figure 9. left: Longitudinal phase-space for positrons right: Average energy and loss percentage top: for electron positron, no Beam Loading consideration bottom: for the first, middle, and last bunches in the train considering Beam Loading, (new optimization)

with significant impacts observed on the positron bunches with large energy spreads and bunch length. The simultaneous presence of both electron and positron beams introduces significant challenges, particularly concerning Beam Loading effects. However, by optimizing phase settings and gradients, these effects can be mitigated, leading to improved Linac performance.

Further studies are needed to refine the optimization process, particularly in compensating for bunch-to-bunch variations and improving the yield in the presence of Beam Loading. Additionally, exploring electron behavior within the capture Linac and their impact on the Beam Loading effect will provide deeper insights into enhancing performance.

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