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COUPLING BETWEEN TRANSVERSE AND LONGITUDINAL BEAM DYNAMICS IN THE FIRST-STAGE CLIC DECELERATOR

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Abstract

In this paper we present the first results of full 6D multi-bunch tracking through the new Drive-Beam decelerator lattice for the first-stage of the Compact Linear Collider (CLIC). Using the new PLACET3 tracking code, we evaluate the coupling between transverse and longitudinal dynamics in the lattice finding an indirect impact of the Drive-Beam's transverse emittance on the Main-Beam performance.

INTRODUCTION

The Compact Linear Collider (CLIC) project [1, 2] is unique in the usage of a two-beam acceleration scheme in which a Drive-Beam travels through a decelerator sector parallel to the experimental Main-Beam Linac in order to power the latter, as shown in Fig. 1. The power extraction is performed by specialized Power Extraction and Transfer Structures (PETS), which provide the RF power to the Main-Beam RF accelerating structures. This project will be implemented in three energy stages aiming at different physics experiment goals ranging from a Higgs factory and top quark mass measurements in the first stage at a centre-of-mass (c.o.m.) energy of 380 GeV, to beyond-standard-model searches in the third stage at 3 TeV c.o.m. energy.

In this paper, we present the new decelerator lattice for the first stage of CLIC developed using the tracking code `PLACET3` [3]. Since the Drive-Beam is not an experimental line, it is somewhat unique in that its requirements for the longitudinal plane are much more restrictive than for the transverse plane. However, as we will show when performing full 6D tracking simulations, one can observe a significant coupling between transverse and longitudinal dynamics in this beamline.

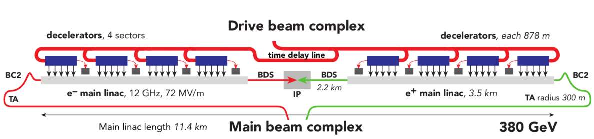

Figure 1: Schematic of the first-stage CLIC main tunnel.

FIRST-STAGE DECELERATOR LATTICE

All decelerator sectors consist of a FODO lattice with decreasing quadrupole strength to match the reduction in beam energy, and between one and four PETS within each FODO cell. The PETS distribution per cell in each decelerator changes to match the power needs of the parallel section of the Main-Beam linac. However, for our studies, we have created a 611 m lattice with four PETS in each cell. The 90% energy extraction requirement fixes the total number of PETS. While the third-stage decelerator lattice has been established since [4], a new lattice is required due to the differences in PETS number and length (L_{PETS}), as well as beam energy. A full set of parameters is given in Table 1.

Table 1: Key CLIC Decelerator Parameters

	First-Stage	Third-Stage
Main-Beam Energy	380 GeV	3 TeV
Main-Beam Gradient	72 MV/m	100 MV/m
Drive-Beam Energy	1.9 GeV	2.4 GeV
Drive-Beam Charge	8.4 nC	
Drive-Beam Frequency	11.994 GHz	
Drive-Beam train	244 nm	
Drive-Beam bunch length	1.00 mm	
Decelerator sectors	8	50
Max decelerator length	878 m	
PETS per decelerator	1216	1492
Cells per PETS	33	34
PETS length	206 mm	213 mm
PETS aperture radius	11.5 mm	
PETS fundamental mode	11.994 GHz	
PETS R/Q	1.15 kΩ	
PETS group velocity	0.4529 c	
Max extracted energy	90 %	

ENERGY EXTRACTION

Using `PLACET3`, we have tracked a Drive-Beam train through the decelerator simulating the momentum loss due to their longitudinal wakefields in the PETS. For any given bunch, the generated wakefield is capable of affecting trailing bunches in the PETS for

$$t_{\mathrm{wake}} = \frac{L_{\mathrm{PETS}}}{c} \frac{1-\beta_g}{\beta_g} = 831\,\mathrm{ps},$$

where β_g is the relativistic group velocity. This is such that each bunch affects nine trailing bunches, so the 2928 bunch-long train reaches a steady state at bunch 10, as shown in Fig. 2. The behaviour of the first nine bunches is consequently not representative of the overall dynamics of the beam. Therefore, from now on, we will use bunch 12 to accurately represent the dynamics of the steady state along the pulse.

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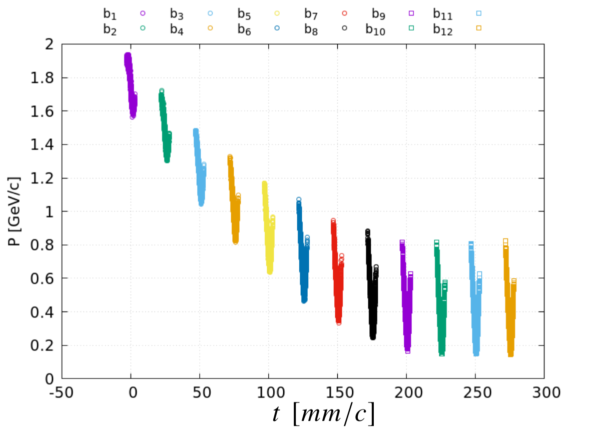

Figure 2: Longitudinal profile at the end of the accelerator of a 0-energy-spread, 0-emittance Drive-Beam pulse.

LATTICE MATCHING

In order to maintain a periodic FODO lattice in a beamline with decreasing energy, one must decrease the quadrupole strength accordingly. While for the third-stage lattice, this was done through an analytical estimation of momentum loss (we present the results in [3]), for the first stage, we instead established the reference momentum numerically from the tracking results.

In Fig. 2, we show the final beam profile of the first few bunches of the train. These results were obtained without initial energy spread (δ) and zero emittance in both transverse planes. Each bunch presents only a Gaussian longitudinal distribution with $\sigma_z = 1$ mm. As the train travels through the decelerator, the wakefield effect does not have the same magnitude across the length of the bunch, inducing a z-P correlation that, for the steady-state, places the core of the longitudinal distribution near the minimum of momentum, with both its head and tail being local maxima.

Figure 3 shows the evolution of the momentum distribution for bunch 1, bunch 3 and the steady-state (bunch 12).

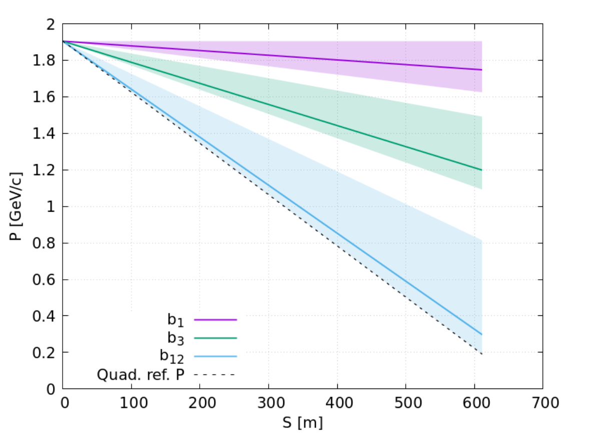

Figure 3: Momentum average (opaque line) and 3-σ distribution along the decelerator. The dashed line denotes the quadrupoles' reference momentum, P, for the FODO lattice.

Since the minimum of the distribution is near the center of the longitudinal distribution, the mean momentum is also close to the minimum. We can use said minimum as the reference momentum for the quadrupoles in our FODO lattice. Since all particles have greater or equal rigidity than this reference, all particles will experience sufficient focusing from the FODO cells.

LONGITUDINAL SLIPPAGE

Though we generally consider the transverse and longitudinal dynamics as uncoupled, across a long enough beamline this approximation may no longer hold. Even if we can safely approximate the beam velocity to c at ultra-relativistic velocities, individual particles with different transverse offsets will travel through shorter or longer pathways as shown in Fig. 4, leading to a mild longitudinal delay of the particles travelling longer paths when compared to those in the center of the phase-space. `PLACET3` allowed us to compute this effect in the PETS of the decelerator lattice for the first time, and evaluate its significance for CLIC's performance.

Bunch Length

The path length differences between particles lead to a cumulative increase of bunch length (σ_z). In Fig. 5, we present the tracking results for steady-state bunches with initial transverse normalized emittance: 100, 120, 150, and 180 μm. The results are expressed as the relative error to the nominal 1 mm bunch. An upper limit to coherent bunch-length error ($\Delta\sigma_z$) has been established as 1% in [5]. For the

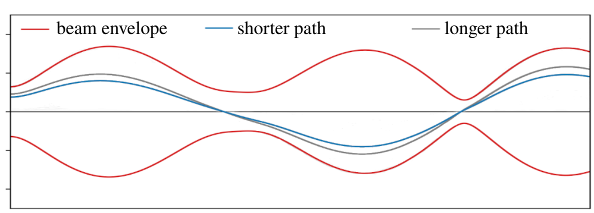

Figure 4: Schematic representation of path length differences between two particles in a beam.

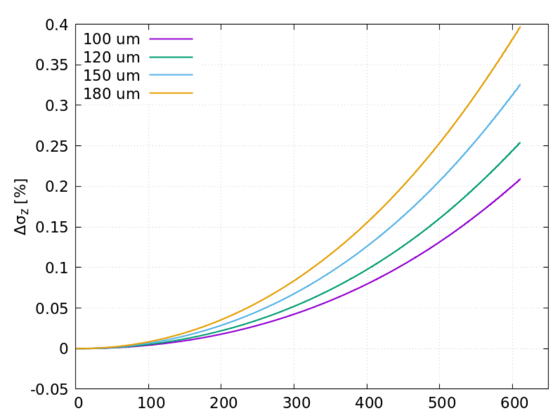

Figure 5: Bunch length increase along the decelerator for different initial transverse emittance values.

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nominal transverse emittance of 150 μm, the maximum $\Delta\sigma_z$ is one third of the established tolerance limit. This coupling should, therefore, not present sufficient impact to hinder RF performance. We do note that the four different decelerator lattices, which, by virtue of having open PETS slots to match the Main-Beam linac spacing, are up to 30% longer than this test. A future study of all four lattices is required to ensure the tolerance limit is not exceeded.

Extracted Power

The efficiency of power extraction in the PETS is proportional to a form factor the longitudinal distribution $F(\lambda(z))$ and the structure design has been optimized such that, for a $\sigma_z = 1$ mm Gaussian distribution, $F(\lambda(z)) = 96.9$. This determines why the tolerances in σ_z are so strict. It is, however, worth noting that as the momentum profile of the beam changes and becomes correlated to z, the difference in rigidity along the longitudinal profile induces a slight variation in the longitudinal distribution $\lambda(z)$, which in turn alters the form factor. To account for this variation, the PETS element in PLACET3 evaluates power extraction directly from the decrease in beam energy instead of relying on $\lambda(z)$-dependent analytical formulae. As such, we observed that the power extracted in the first decelerator PETS is 16.1 MW per steady-state bunch, which corresponds to 133 MW per PETS since multiple bunches travel inside the PETS. Using that as a benchmark, we produced Fig. 6, which directly shows the change in power extraction as it is affected by the evolution of σ_z and the form factor. Our results show that, for the nominal beam, there is minimal variation in power extraction along the beamline, with a maximum deviation of 0.15 ‰. Using PLACET3, future tolerances can be established directly as a measure of extracted power rather than assuming any given distribution and associated form factor.

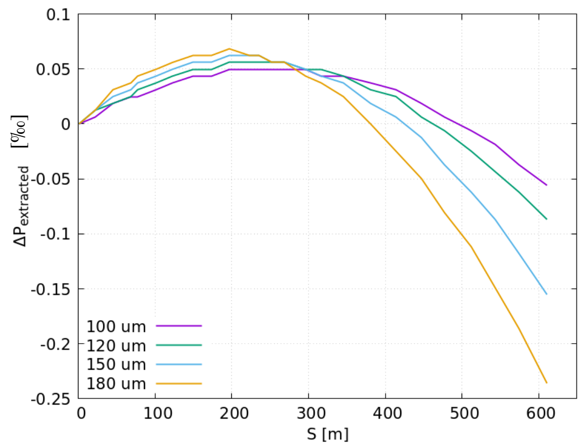

Figure 6: Difference in extracted power from one steady-state bunch per PETS along the decelerator.

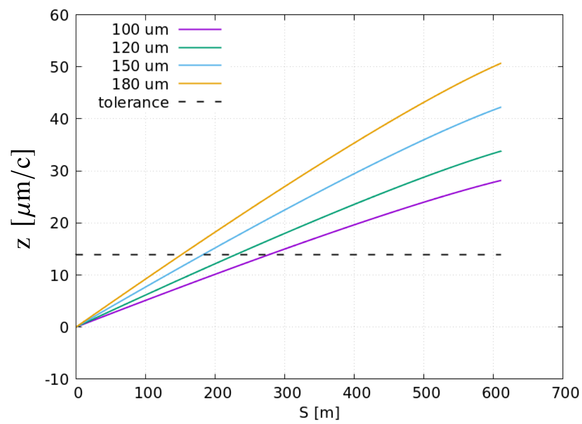

Figure 7: Longitudinal slippage along the decelerator for different initial transverse emittance values.

Bunch Phase

For the previous 30 GHz CLIC design, the effects of betatron oscillations due to transverse jitter were thoroughly studied [6] leading to the establishment of a tolerance of 0.2° X-band for coherent phase errors [5]. Unlike jitter, static effects can be nullified by the RF transport. We assume this mitigation to be done at commissioning.

Figure 7 shows the mean longitudinal slippage for a centered steady state bunch with initial normalized transverse emittance of 100, 120, 150, and 180 μm. It also shows the phase tolerance in units of μm/c, which is surpassed for any of the studied emittances, confirming the need for phase shit mitigation. A more concerning issue is the correlation between this effect and transverse emittance, since the latter is typically highly dependant on operational conditions. A future study of both dynamic and static effects is required to establish new tolerances including emittance tolerances.

CONCLUSION

We presented the first implementation of the decelerator lattice for the first stage of CLIC. Using the new features of the tracking code PLACET3, we performed the first studies of said lattice, focusing on the coupling between transverse and longitudinal dynamics. We showed that longitudinal slippage of high transverse emittance particles significantly affects the bunch length, form factor $\lambda(z)$, and power extraction. Still, that effect is within the established tolerances ($\Delta\sigma_z < 1$ %) of CLIC. However, we also observed a delay in the phase of the bunch, which is three times the established tolerance by the end of the beamline. Though it is possible to correct static phase errors during commissioning, this phase delay is emittance-dependent, which limits operational options. Future studies of static and dynamic effects are required to establish up-to-date tolerances for this lattice.

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