SCALING LAWS OF WAKE FIELD EFFECTS DUE TO GRADIENT CHANGES IN THE CLIC MAIN LINAC

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Abstract

The main linac of CLIC is designed to maximize the transportable bunch charge, since this parameter determines the energy efficiency of the CLIC accelerating structures. The bunch charge is limited by short-range wake field effects, which increase the projected beam emittance. For the main linac cost optimisation, it is important to understand how the charge limit scales with the change of the gradient of the accelerating structures. In this paper, we determine such a scaling law via simulations studies. It is shown that from different possible scenarios, the charge limit for a lower gradient CLIC structure scales advantageous and a relatively high charge can be used.

INTRODUCTION

The bunch charge N is one of the most important design parameters of CLIC. This is due to the fact that the whole design is driven by the need to achieve high enough power efficiency. For the normal conducting accelerating structures used at CLIC, this directly leads to the need of high average beam current I_T during a bunch train and therefore high bunch charge. This can be seen from the relation that connects the RF power that is transferred to the beam P_{beam} and the power P_{wall} lost in the walls of a normal conducting accelerating structure (see [1])

$$\frac{P_{beam}}{P_{wall}} = \frac{R_S I_T}{G},\qquad(1)$$

where R_S is the shunt impedance, which is determined by the geometry and the material properties of the accelerating structure, and G is the acceleration gradient. Higher bunch charge (and therefore higher RF efficiency) can be used to produce more luminosity with the same electricity cost, or the same luminosity with lower electricity costs. It is therefore essential for CLIC to maximise N.

In the case of CLIC, the maximal bunch charge is limited by short-range wake field effects in the main linac. These effects will be explained in the following section. The main linac of CLIC has been especially designed to maximise the charge transport by using the strongest possible focusing for a given filling factor. This results in small β-functions and therefore small beam offsets in the accelerating structures. Additionally, the bunch parameters are adjusted to allow for a wake field effect mitigation method called BNS damping [2] that will also be explained in the next section. With this combination of beam line design and bunch parameters choice, the maximum bunch charge N_0 has been determined in simulations [3] to be 3.72×10^9 particles.

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In the currently on going re-baselining of CLIC, the initially determined beam parameters are revised to minimise the overall cost. A cost model has been developed, which includes construction costs of main linac and the drive beam complex. A large number of acceleration structures is tested with this cost model to determine the optimal RF structure design. An essential information in this model is the maximal bunch charge N_1 that can be used for a given structure. Hence, an analytic scaling law of N_1 in dependence of the gradient G_1 is needed and will be established in this paper.

To obtain such a scaling law, we compare the current baseline design with the charge limit N_0 and a gradient G_0 of 100 MV/m with a design that uses a structure with half the gradient G_1 of 50 MV/m. To determine N_1 for a structure with G_1, a different main linac lattice has to be used. For that reason, the baseline design has been adapted, by basically doubling the number of accelerator modules. With this approach the β-function has the same amplitude as for the baseline design, but is stretched in the longitudinal direction by a factor two. For this prolonged linac, the maximal charge N_1 has been evaluated in this paper via simulation studies. Two different imperfections have been considered for this evaluation. Additionally, when the maximal bunch charge is determined, it is not sufficient to only change the charge independently, but also the bunch length has to be adapted. This fact together with the adaptation procedure will be explained in the next section. Finally, a simple charge scaling law will be determined form the simulation findings.

BACKGROUND

Limitations Due to Short-range Wake Fields and BNS Damping

Short-range wake fields in the longitudinal as well as in the transversal direction limit the maximal bunch charge in the main linac of CLIC. The longitudinal wake fields, induced by the head of the bunch, act on its tail by applying a force approximately proportional to $W_{long}(1/\sigma_z)N$, where W_{long} is the longitudinal wake potential, and σ_z is the bunch length. For the very short bunches used at CLIC, the longitudinal wake potential gets smaller for longer bunches, which is symbolised by the term $1/\sigma_z$. The longitudinal wake field causes the tail of the bunch to lose energy compared to the bunch head. This results in a correlated energy spread σ_E. This energy spread has to be kept smaller than 0.35%, mainly due to the limited energy acceptance of the beam delivery system of CLIC. Therefore, one tries to compensate the wake field induced σ_E by accelerating the bunch slightly off crest with an angle ϕ. To not decrease the effective acceleration gradient too much, ϕ is kept below 8 degrees. This complex interplay is visualised in Fig. 1.
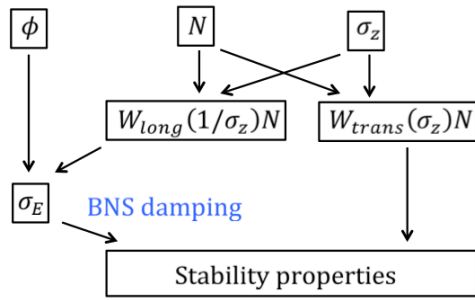
Figure 1: Interplay of the different beam parameters that determine the beam stability due to wake fields.

Not only longitudinal but also transversal wake fields limit the maximum charge. The transverse wake fields induced by the head of the bunch act on the tail of the bunch in form of a defocusing force proportional to $W_{trans}(\sigma_z)N$, where W_{trans} is the transverse wake potential. This defocusing force will cause the head and the tail to move on different trajectories. If this effect is strong enough, the beam emittance is strongly increased, which is known as the beam breakup instability (BBU).

The BBU instability can be mitigated by applying a technique called BNS damping [2]. The BNS damping is based on the idea that the defocusing force of the wake field can be compensated, if the bunch of the tail is effectively stronger focused then the head. This can be achieved, if the bunch tail has lower energy than the head. Fortunately, this is the case, since the longitudinal wake fields create such an energy chirp. The stronger the energy chirp, the higher transverse wake field kicks can be compensated. For the CLIC main linac the parameters have been adjusted to optimally facilitate BNS damping. This is also reflected in the fact that the β-function of the lattice is scaled as $\sqrt{E}$, which can be shown to be a requirement for BNS damping equally along the main linac for bunches with constant σ_E.

Adaptation of Beam Parameters

When determine the maximal bunch charge, it is not possible to simply change the bunch charge in simulations. As has been explained above, not only the transverse wake field effect would be influenced, but also the beam energy spread σ_E via the longitudinal wake fields, which is not acceptable. Therefore, if the bunch charge N is changed, the bunch length σ_z has to be adapted such that the longitudinal wake field effect stays approximately constant. For the current studies, this adaptation has been performed with an iterative approach, including the exact wake function and the longitudinal bunch charge profile. Even thought the longitudinal wake field effect can be kept approximately constant, the transverse wake field effect will become stronger with increasing charge and decreasing bunch length. For too high charge values, BNS damping will not work efficient anymore. Which charge and bunch length combination can still be transported by the linac has to be evaluated in simulations.
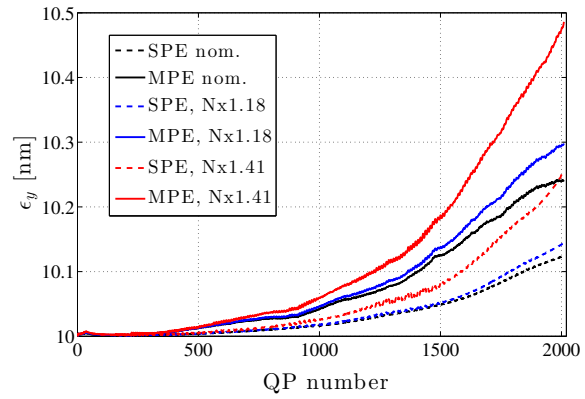

Figure 2: Single (SPE) and multi (MPE) pulse vertical emittance ϵ_y along the nominal main linac of CLIC, due to girder misalignments for different bunch charges.
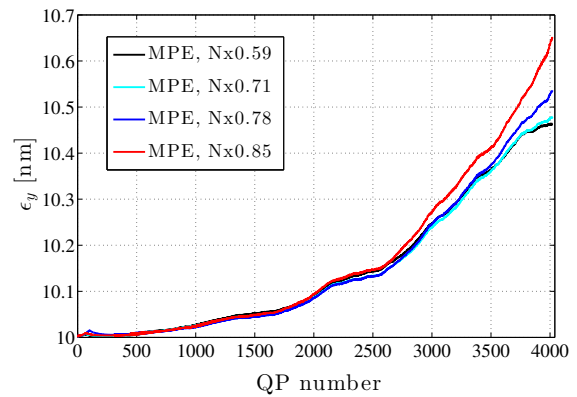

Figure 3: Single (SPE) and multi (MPE) pulse vertical emittance ϵ_y along the prolonged main linac of CLIC, due to girder misalignments for different bunch charges.

SIMULATION RESULTS

To determine the maximal charge N_1, two imperfections have been applied in simulations to the nominal linac and a prolonged version in which the acceleration gradient has been halved. As a simulation code, PLACET has been used [4]. The charge (and the bunch length) in the prolonged linac have been varied until the effect on the emittance was approximately the same as in the nominal linac for the charge N_0. To be able to judge when the behaviours in the two linacs are approximately the same, it is useful to test also the nominal linac not only with N_0, but also with other charge values.

The first tested imperfection is the misalignment of the accelerator girders. Such misalignments can reveal charge limitations due to the BBU instability and incoherent imperfections. As an approximation of the orbit feedback operation, 0.4 s of ground motion of model B10 and a quadrupole stabilisation function of type V1 (see [5] for more details) have been used. The results are depicted in Fig. 2 and 3 for the nominal and the prolonged main linac respectively. In
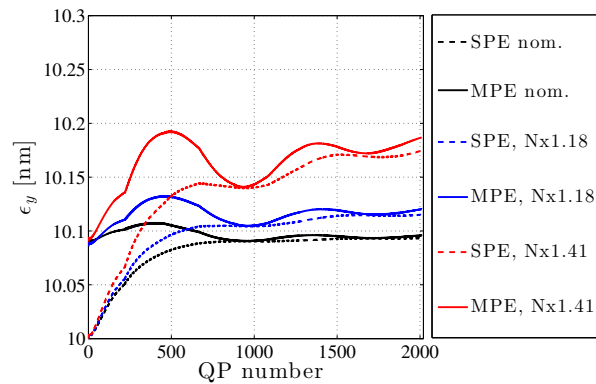
Figure 4: Single (SPE) and multi (MPE) pulse vertical emittance ϵ_y along the nominal main linac of CLIC, due to initial beam jitter for different bunch charges.
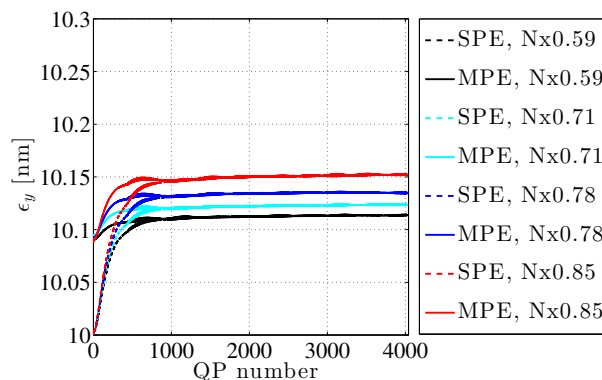

Figure 5: Single (SPE) and multi (MPE) pulse vertical emittance ϵ_y along the prolonged main linac of CLIC, due to initial beam jitter for different bunch charges.

these plots, not only the projected emittance of one bunch (SPE), but also the multi pulse emittance (MPE) is shown. The MPE is the combined projected emittance of 10 simulated bunches and therefore also contains the luminosity relevant beam jitter. For the misalignments, the nominal main linac operates in a regime, where a decrease of the bunch charge, does not lead to a decrease in emittance growth anymore (conservative). The remaining emittance growth is not due to wake fields, but due to dispersive effects. This charge independent, dispersive emittance growth scales as $\Delta \epsilon_D = 0.24 \times G_0/G_1$ [nm]. To stay within this dispersive regime, the maximal charge N_1 for the prolonged linac has to stay below $0.7 \times N_0$. which corresponds to the simple scaling law $N_1 = N_0\sqrt{G_1/G_0}$. This scaling corresponds to the BBU mechanism and is advantageous for the re-baselining, since relatively high bunch charge can be used for lower acceleration gradients.

The second tested imperfection is initial beam jitter at the entrance of the main linac that increases the projected emittance by 1%, from 10 nm to 10.1 nm, which is the maximal allowed value for CLIC. With this imperfections type, it is possible to reveal imperfection limits due to the BBU instability as well as due to imperfect BNS damping. Figures 4 and 5 show the according charge dependent effects along the nominal and the prolonged main linac, respectively. Also here the nominal main linac operates in a regime, where wake field effects are not amplifying the initial beam jitter. Only when about 40% more charge is used, the induced emittance increase is doubled. The behaviour in the prolonged linac differs significantly from the one in the nominal linac. In this case, the emittance increase occurs only at the beginning of the beam line before it reaches a steady state. In the region of emittance growth, BNS damping is not working, since the necessary correlated energy spread is only slowly build up, due to the smaller acceleration gradient. Therefore, one can see an instability at the beginning of the accelerator. The initial oscillations that are amplified by this instability are quickly fully removed by the strong filamentation. This filamentation is stronger in the prolonged linac, since the relative uncorrelated beam energy spread is reduced slower, due to the smaller gradient compared to the nominal case. In general, the effect due to the incoming beam jitter at CLIC is small compared to the imperfections test case and can therefore be neglected.

CONCLUSIONS

In this paper, the dependence of the maximal transportable bunch charge N_1 from the used acceleration gradient G_1 has been studies for the main linac of CLIC. Therefore, a scaled version of the main linac lattice with half nominal gradient was created. In simulations different imperfections have been applied as test cases and the N_1 was determined. Using these findings, it can be concluded that the maximal bunch charge scales as $N_1 = N_0\sqrt{G_1/G_0}$, which allows using relatively high charge compared to the other possible limiting mechanisms. The dependence is an important ingredient for the on going re-baselining of CLIC, which has already led to a significant cost reduction of the project.

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