



Performance of CLIC emittance tuning bumps in a dynamic environment

P. Eliasson*[†] D. Schulte[†]

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Abstract

Previous simulations of the CLIC main linac have shown that the use of emittance tuning bumps as a complement to beam-based alignment is extremely useful for reduction of emittance growth caused by static imperfections. The performance of the tuning bumps may, however, be affected by a wide range of dynamic imperfections. In this paper, the use of CLIC emittance tuning bumps in a noisy environment has for the first time been systematically studied. Element and beam jitter, as well as ground motion and feedback imperfections have been considered. Furthermore, limited emittance measurement precision and also limited mover speed are taken into account.

In the static case, the bumps used in this paper were seen to reduce emittance from 23.8 nm after beam-based alignment to 0.44 nm. For more realistic simulations, including reasonable dynamic imperfections and ground motion described by the ATL model, the lowest achievable emittance growth was approximately 0.63 nm. The additional emittance growth is mainly caused by the direct effect of dynamic imperfections rather than by the interference between tuning bumps and imperfections. Initial studies using a two-dimensional power spectrum to model ground motion indicated similar bump performance. The possibility of using a wide laserwire to provide the bumps with a tuning signal was investigated with good results.

*Uppsala University, Sweden

[†]CERN, Geneva, Switzerland

1 Introduction

One of the major challenges for the future linear collider CLIC [1] is the preservation of emittance in the main linac. Low-emittance beams are necessary to create high-luminosity collisions and consequently favourable conditions for physics experiments. The many elements of the CLIC main linac make emittance preservation a challenging task, and several methods have been developed for element alignment and emittance tuning.

Previous studies [2–5] have shown that in addition to one-to-one correction, dispersion free steering [6], and RF alignment, so-called emittance tuning bumps [2, 5] have to be used to achieve acceptable emittance. The emittance bumps used here are nearly identical to the ones described in [5] and are based on the idea of “trajectory bumps”, see [7, 8]. Emittance tuning bumps consist of knobs and a measurement station. In this paper, each knob controls the vertical position of a large number of accelerating structures, and the effect of using a knob is recorded by measuring the emittance at the end of the linac. During tuning, one knob after the other is adjusted to minimise emittance.

A strategy for design of optimised emittance tuning bumps was recently developed [5]. Ten knobs were constructed using this strategy, and their performance was simulated for 100 static machines with initial misalignments. The emittance reduction capability and convergence speed were seen to be excellent. However, no dynamic imperfections were taken into account during the simulations, and the performance of the bumps may no longer be satisfactory if such imperfections are considered. In this paper, the influence of ground motion, element jitter, beam jitter, and a few other imperfections on CLIC emittance tuning bumps has for the first time been systematically investigated.

The emittance growth caused by different dynamic imperfections was studied in detail in [9] along with the design of an optimised feedback system. Using these feedbacks, the effect of ground motion could be significantly reduced, and the main source of emittance growth was seen to be the direct effect of element and beam jitter. This direct effect is independent of the feedback system used. Jitter was also seen to cause a small amount of indirect emittance growth due to the interference between jitter effects and the feedback system. Here, indirect emittance growth caused by the interference between imperfections and the tuning bumps will also be important. Each imperfection causes a certain variance in the emittance measurement which via the optimisation procedure of the tuning bumps propagates to an uncertainty in the optimal knob settings and consequently leads to a degradation of the bump performance. The resulting emittance growth was determined by simulations and was seen to be small compared to the other sources of emittance growth.

It is, at the moment, not clear how emittance will be measured. The speed and precision of the measurement will affect the performance of the bumps. In this paper, a 3% and a 10% measurement error were tested in order to get an idea of how severe such effects may be. It was assumed that emittance could be measured within a pulse. In [10] it is described how laserwire scanners may be used to measure emittance in the ILC beam delivery system. In [3, 11] it was suggested that two fixed, wide (size of an ideal target

beam) laserwires could be used to measure emittance. Simulations using such laserwires were also performed in this paper. However, the actual implementation of this laserwire system has still not been investigated.

During the simulations, ground motion was described using the simple ATL model [12]. A few simulations were also carried out using a more accurate space-time power spectrum [13]. All results were obtained using the 1500 GeV lattice described in [14]. The most important beam parameters are summarised in Table 1. Observe that during 2007

Table 1: CLIC beam parameters.

Parameter	CLIC
Initial energy [GeV]	9
Final energy [GeV]	1500
Initial vertical emittance [nm]	5
Particles per bunch [10^9]	2.56
Bunch length [μm]	30.8
Pulse repetition rate [s^{-1}]	150

the CLIC parameters changed. In order to facilitate the comparison with previous emittance preservation studies, all simulations performed in this paper were based on the old parameter set.

2 Static Alignment and Tuning

As initially described, both beam-based alignment and emittance tuning bumps are necessary to preserve emittance in the CLIC main linac. The performance of both these methods have been studied in detail in several previous papers. During these studies, the impact of dynamic imperfections on emittance tuning bumps was, however, not taken into account. Dynamic effects during beam-based alignment were studied in [15], but for different optics and beam parameters as compared to this paper.

In [5] the design of emittance tuning bumps was studied in detail. Theoretical considerations showed that previously studied bump configurations could be significantly improved in terms of emittance reduction performance and convergence speed. Simulations confirmed the excellent performance of the new bumps. The optimised knobs were constructed by representing the state of the machine and each knob in a coordinate space which was normalised such that emittance is proportional to squared distance from the origin. Using singular value decomposition, the conjugate (non-interfering) directions along which emittance growth is most efficiently reduced could be identified.

2.1 Performance of bumps in static environment

A set of ten optimised knobs, each controlling the vertical position of 662 accelerating structures, was constructed in [5]. It was assumed that the beam was resteeered using one-to-one steering after each knob adjustment. In reality it would be too time-consuming

to do a one-to-one steering after each knob change, and in this paper it was instead assumed that every knob change is accompanied by a feedback restearing. This changes the effect of a structure displacement and a slightly different set of knobs is obtained. The performance of the new knobs was seen to be nearly identical to what was obtained when assuming one-to-one correction. In this case, only the eight most efficient knobs were used, since the other two were seen to offer little emittance change for reasonable knob changes. If the limited emittance measurement precision had been taken into account, the tuning of these less efficient knobs would be dominated by noise. For both types of bumps, a set of 100 initially misaligned machines was tuned, and the average emittance growth calculated. The initial misalignments correspond to what remains after beam-based alignment of a static prealigned machine, cf. [5]. Initially the emittance growth was 23.8 nm, which is far above the 5 nm emittance growth budget for the main linac. Using the emittance tuning bumps, the emittance growth is reduced to 0.44 nm both in case of one-to-one steering and in case the feedback system is used. The convergence is also seen to be excellent, see Fig. 1. In order to ensure that the

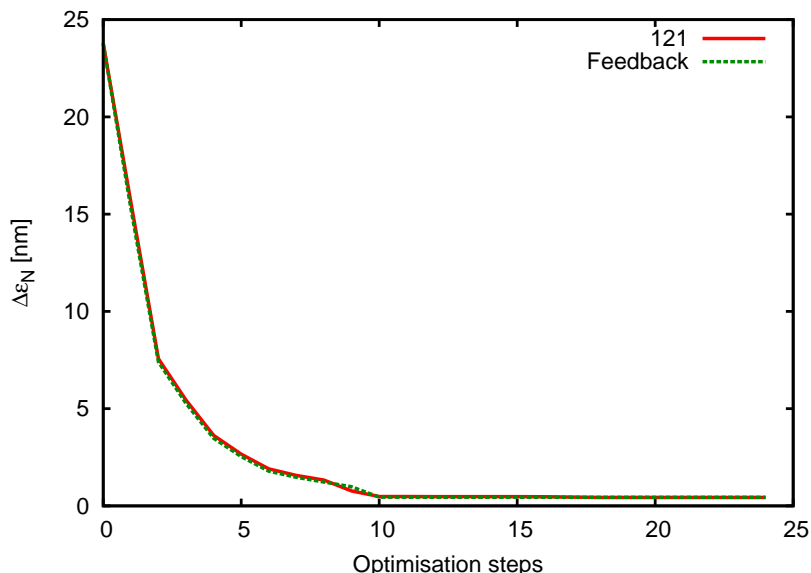


Figure 1: Performance of bumps accompanied by one-to-one steering as compared to bumps accompanied by feedback restearing.

accelerator structure displacements needed to tune the linac are of acceptable magnitude, the displacements for the final knob settings were determined for each machine. A few tens of μm is considered acceptable, which is also the case, see Fig. 2. The obtained displacements are very similar to what was obtained for the bumps in [5].

Observe that during the simulations described above, dynamic effects were neglected both during the initial beam-based alignment and during the bump tuning. While these results are very promising, the performance may change when dynamic effects are included. In the next few sections the additional emittance growth due to dynamic effects during the bump tuning phase will be studied.

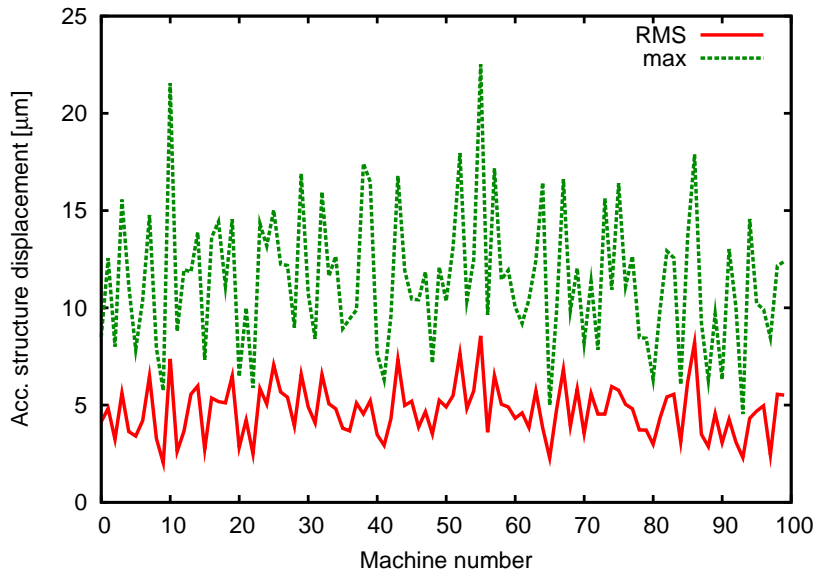


Figure 2: RMS and maximum displacements for the 662 accelerating structures controlled by eight knobs after correction of each of 100 seeds.

3 Emittance tuning in a dynamic environment

The performance of the bumps described in Sec. 2 was excellent as long as the tuning was carried out in a static environment. Here, the degradation of the performance caused by dynamic imperfections will be studied. To find the major factors that limit the performance of the tuning bumps, this will be done stepwise. First, the bumps were tested in a noisy environment with an initially ideal machine. Then the effect of bump tuning with dynamic imperfections was tested for machines that were already beam-based aligned and emittance-tuned until convergence. Finally, the tuning bumps were applied to beam-based aligned machines with dynamic imperfections taken into account during the whole tuning bump procedure.

During all simulations it is assumed that the response matrix containing the BPM response to a knob change is perfectly known. In this way, the beam may be automatically resteered when a knob is turned, without actually using any BPM readings. Errors in the knob response matrix may require further studies. An alternative way of resteeering the beam could be to apply the feedback with gain $g = 1$ directly after each knob change. This would, however, introduce misalignments due to eg. jitter and finite BPM resolution. By giving the feedback system some time to correct the so introduced misalignment with a lower gain, the tolerance to jitter and BPM resolution may still be acceptable. Both methods have their imperfections, and possibly a combination would be the most robust option.

As described in [5], the optimal knob settings are obtained by fitting a quadratic function to emittance measurements taken for different knob settings. Here, each fit was initially based on eight measurements. The knob settings, and consequently the acceler-

ating structure displacements, were changed back and forth while measuring emittance at each pulse, see Fig. 3. During all simulations in this paper, it was assumed that

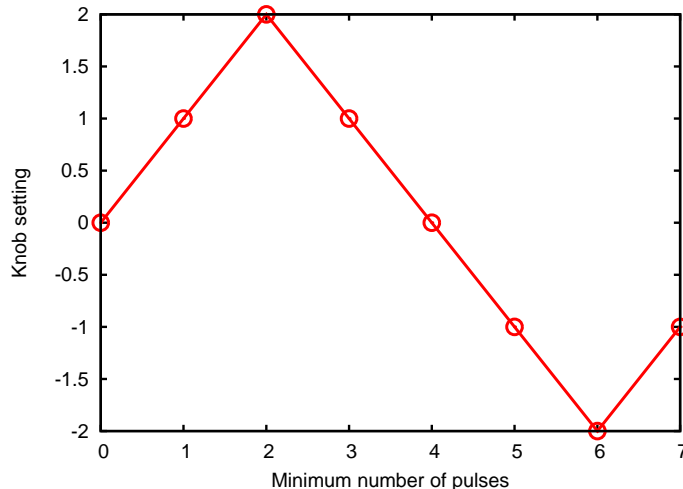


Figure 3: The tuning bumps were optimised by measuring the emittance for a number of knob settings. The optimal setting was then obtained by fitting a square function to the obtained data.

the accelerating structures could be displaced by maximum $1 \mu\text{m}/\text{pulse}$. For some of the weaker knobs, the accelerating structure displacements needed to change emittance considerably (relative to noise level) are of the order of $10 \mu\text{m}$. Consequently, the optimisation of the weaker knobs takes more time than the optimisation of the more efficient ones.

3.1 Tuning bump performance for ideal machines

In order to get an idea of how sensitive tuning bumps are to dynamic imperfections, they were first tested in an ideal machine. Without dynamic imperfections, the bumps will not cause any emittance growth. If dynamical effects are included according to Table 2 and the optimised feedback system is activated, the bumps will, however, be

Table 2: Magnitudes of the dynamic imperfections.

Imperfection	Magnitude
Quadrupole jitter (σ_q)	1 nm
Accelerating structure jitter (σ_s)	1 nm
Injected beam jitter (σ_b)	$0.1 \mu\text{m}$
BPM resolution (σ_{BPM})	$0.1 \mu\text{m}$
Ground motion (ATL parameter A)	$0.5 \times 10^{-6} \mu\text{m}^2/\text{s}/\text{m}$

disturbed. Simulations of 100 random seeds showed an average emittance growth of 0.18 nm after four tuning bump iterations. The inevitable emittance growth caused

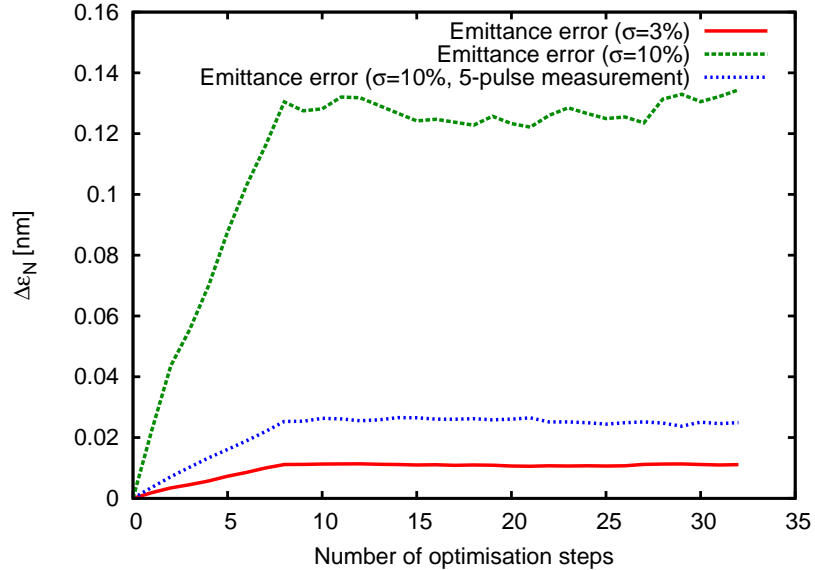


Figure 4: Emittance growth caused by the tuning bumps themselves when emittance noise is taken into account.

by dynamic imperfections alone was shown to be ≈ 0.16 nm, in agreement with results in [9]. The additional emittance growth caused by the interference between imperfections and the bumps is apparently ≈ 0.02 nm. Similarly, the influence of imperfect emittance measurements was studied. The bumps were used on an ideal machine with emittance noise as the only imperfection. While a 3 % noise was seen to cause little (≈ 0.01 nm) additional emittance growth, the effect of a 10 % noise was not negligible (≈ 0.13 nm). Obviously, the bumps can not accurately determine the optimal knob settings for a 10 % emittance measurement error. Observe, that compared to the emittance growth reduction from 23.8 to 0.44 nm for ideal bumps, the imperfections cause small changes and the bumps will still be very efficient. However, in order to improve the tolerance to emittance noise, more measurement data was collected during each optimisation step. This was done by measuring emittance during five pulses (instead of one) at each point shown in Fig. 3. In this way, the measurement precision may in principle be improved by a factor $\sqrt{5}$. Since the measurement procedure becomes slower, the effect of ground motion could possibly have a stronger impact than before. Thanks to the efficient feedback system, this was, however, not the case.

An alternative method could be to spread out measurements along the path in Fig. 3 instead of stopping at some points. For some of the weaker knobs, the change between each knob setting require structure movements which can not be performed from one pulse to another (assuming $1 \mu\text{m}/\text{pulse}$ movers). In this case, it would be natural to measure at intermediate positions as well. This fact was not used during the simulations of this paper.

By using five times more measurements, the sensitivity to emittance noise was considerably reduced, see Fig. 4. It was similarly seen that the indirect effect of the dynamic

imperfections of Table 2 was reduced from 0.02 nm to nearly zero. Observe that while the complete tuning procedure was seen to require roughly 1850 pulses (≈ 12 seconds) when only one measurement per knob setting was used, it required 2850 pulses (19 s) in case of five measurements per setting.

Simulations of tuning bumps for an initially ideal linac, with all dynamic imperfections and a 10 % emittance noise, showed that the dominating source of emittance growth is the direct effect of dynamic imperfections (0.16 nm), see Fig. 5. During these simulations, five emittance measurements were performed for each knob setting.

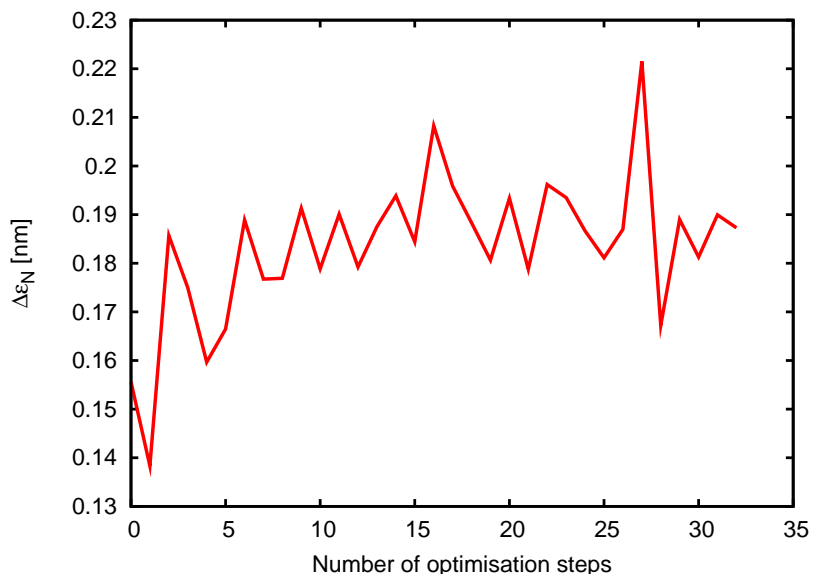


Figure 5: Average emittance growth for an initially ideal linac as the tuning bumps are applied with dynamic imperfections and emittance noise is taken into account. In total 100 random seeds were simulated. The major part (0.16 nm) of the emittance growth is caused by the direct effect of dynamic imperfections.

3.2 Tuning bump performance for tuned machines

So far no initial static imperfections have been considered. The same simulations as above were carried out, with the only difference that the machines were initially beam-based aligned and emittance-tuned. In this way, a lower limit to the total emittance growth can be determined.

As previously shown, the average final emittance growth for 100 random machines corrected using tuning bumps is 0.44 nm if no dynamic imperfections are taken into account. If the bumps are left to continue running, but now with dynamic imperfections and a 10 % emittance error, the emittance growth will increase. The result was seen to be very similar to what was obtained for an initially ideal machine, apart from a constant difference of 0.44 nm, see Fig. 6. Consequently, it may be concluded that the indirect effect of imperfections and bump tuning is not affected by including the static imperfections.

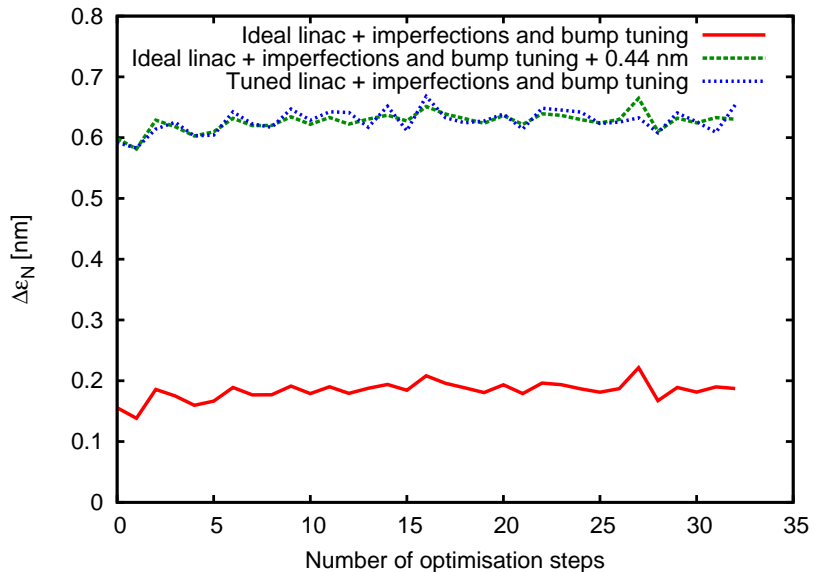


Figure 6: Emittance growth during bump tuning. The additional emittance growth for a tuned linac as compared to an ideal linac is seen to be 0.44 nm, i.e. exactly what is caused by the initial static imperfections. The emittance growth of 0.63 nm for the tuned linac specifies a lower limit for the performance that may be obtained when dynamic imperfections are taken into account during the whole tuning bump procedure.

3.3 Tuning bump performance for beam-based aligned machines

During the last step of this investigation, dynamic imperfections and emittance errors were included during the whole tuning bump procedure. In total 100 machines aligned with beam-based alignment were tuned using the bumps. The initial emittance growth of 23.8 nm was decreased to 0.64 nm in four iterations (32 optimisations steps). The intermediate results obtained above were seen to give a very accurate prediction of the bump performance as all effects are included, see Fig. 7. The final emittance growth of 0.64 nm is caused by static misalignments (0.44 nm), dynamic imperfections (0.16 nm), and interference between bumps, emittance noise and other dynamic imperfections (0.04 nm). In order to ensure that the ATL model does not give overly optimistic results, a single ground motion seed described by a two-dimensional power spectrum according to model B (intermediate noise level) [16] was tested. Using the tuning bumps to correct the 100 machines with dynamic imperfections as above, but with the same model B ground motion seed for all machines, it was seen that the bump performance is nearly identical to before, see Fig. 8. A closer inspection, however, showed that the average final emittance growth in this case is 0.68 nm. It may seem that the emittance growth caused by interference between bumps and imperfections has been doubled.

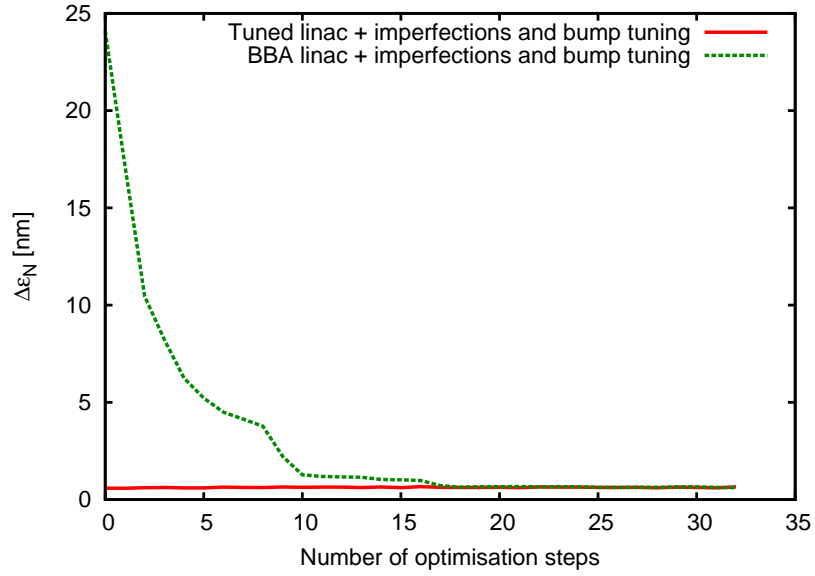


Figure 7: Emittance growth variation during four iterations (32 optimisation steps) taking dynamic imperfections and a 10 % emittance error into account. The emittance growth of a beam-based aligned (BBA) linac is seen to converge to the same level as a tuned linac.

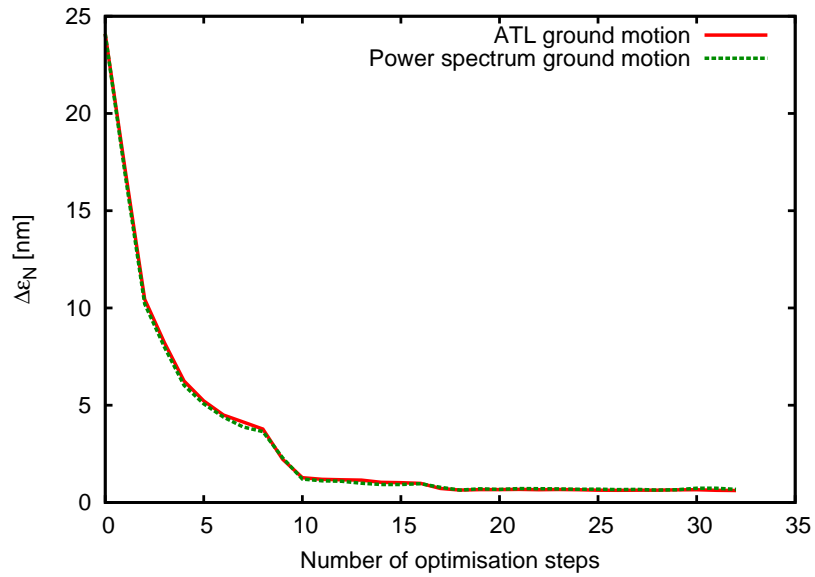


Figure 8: Average emittance growth during bump tuning for two different ground motion models. The ATL model parameter was $A = 0.5 \times 10^{-6} \mu\text{m}^2/\text{s}/\text{m}$ and the power spectrum was based on model B [16]. In case of the power spectrum model, the same seed was used for all 100 machines corrected.

4 Using wide laserwires for beam quality determination

As described in [3, 11], laserwires could in theory be used to get a measure of the quality of the beam. The idea, in short, consists in placing two laserwires separated by a phase advance of 90° in a diagnostics section downstream the main linac. Each laserwire would have a Gaussian transverse profile of similar size as an ideal target beam. Consequently, it would be wide as compared to the laserwire of a scanner. In addition, this wide laserwire would have a fixed position (or possibly slowly changing to compensate for beam drifts due to ground motion). When the beam crosses the laserwires, back-scattered photons could provide a tuning signal for the bumps. Obviously, the knobs would in this case be adjusted to maximise the signal. When all dynamic imperfections were included and a signal error of 10 % was taken into account, these tuning bumps could reduce emittance growth to 0.78 nm, see Fig. 9. Observe that for this laserwire signal,

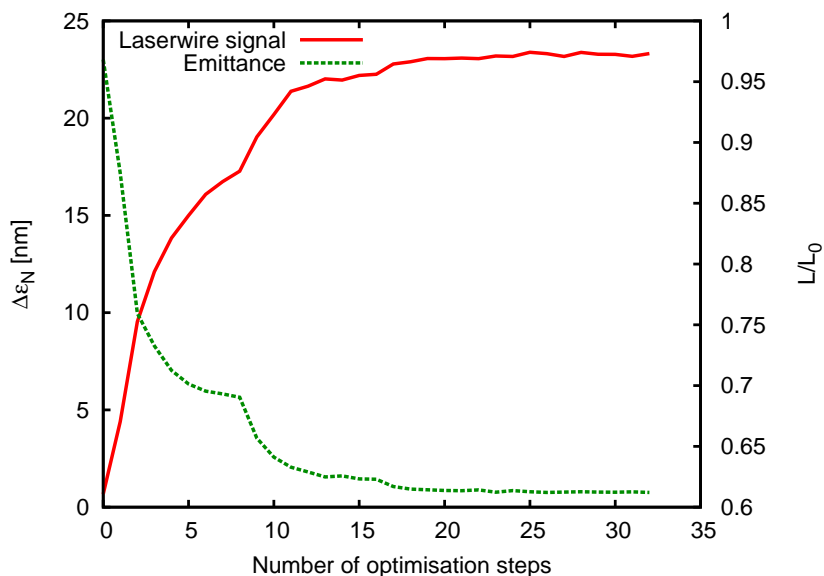


Figure 9: Emittance growth and laserwire signal vs number of optimisation steps. The laserwire signal was used as a tuning signal, while the emittance was measured but never used.

a 10 % signal error is more severe than for an emittance signal. The results shown in Fig. 9 were obtained using ten measurements per knob setting as opposed to five before. The whole tuning procedure required 4100 pulses (≈ 27 s).

5 Conclusions

The influence of dynamic imperfections on emittance tuning bump performance in the CLIC main linac has for the first time been systematically investigated. Quadrupole, accelerating structure, and beam jitter were considered. In addition, ground motion and feedbacks with imperfect BPMs were taken into account. The bumps were also

imperfect in terms of limited mover speed (maximum 1 μm structure displacements per pulse) and emittance measurement precision (10 % noise).

The tuning bumps were first shown to reduce the average emittance growth of 100 machines from 23.8 nm after beam-based alignment to 0.44 nm after tuning in case none of the imperfections were included. It was then shown that when all imperfections were included, and the tuning procedure was modified to improve stability, the achievable emittance was instead 0.64 nm. The contributions to this total emittance growth is 0.44 nm due to static misalignments, 0.16 nm due to direct effect (independent of bump tuning) of dynamic imperfections, and 0.04 nm due to interference between bumps and dynamic imperfections. Obviously, this last effect is not very severe as long as the tuning procedure is properly implemented.

The first simulations were all carried out with ground motion described by the ATL model (model parameter $A = 0.5 \times 10^{-6} \mu\text{m}^2/\text{s}/\text{m}$). The bump performance with ground motion described by a two-dimensional power spectrum was also investigated. The final emittance growth was in this case seen to be 0.68 nm. The interference contribution is in this case 0.08 nm, i.e. twice as large as before. Observe, that in this case the same ground motion seed was used for all 100 machines.

A wide laserwire was tested as a means for determination of beam quality. It was shown that such a measurement station could in theory work very well. The bumps using a laserwire signal were more sensitive to noise, but by adapting the tuning procedure, these bumps could reduce emittance growth to 0.78 nm with a 10 % laserwire measurement error and dynamic imperfections taken into account.

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