# IMPLICATIONS OF A CURVED TUNNEL FOR THE MAIN LINAC OF CLIC*

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### *Abstract*

Preliminary studies of a linac that follows the earth curvature are presented for the CLIC main linac. The curvature of the tunnel is modeled in a realistic way by use of geometry changing elements. The emittance preservation is studied for a perfect machine as well as taking into account imperfections. Results for a curved linac are compared with those for a laser-straight machine.

## INTRODUCTION

At CERN a multi-TeV electron positron collider is under study, the compact linear collider (CLIC). It is based on normal conducting high frequency RF technology, which can provide the high gradient required. The RF power that is used to accelerate the main beam is produced by decelerating a high current low energy drive beam that runs in parallel with the main beam.

The preservation of the beam emittance in the main linac is a challenging task and is therefore being studied in detail. An important source of emittance dilution are the wakefields in the main linac accelerating structures. Their effect can be reduced by using a strongly focusing lattice. This in turn makes the beam more sensitive to dispersive effects. In order to provide optimum conditions for the beam it is envisaged to have a laser-straight main linac tunnel; this minimizes the dispersive effects.

The choice of the tunnel layout has a strong impact on the cost of future linear colliders. Depending on the geology it may be cheaper to use a tunnel that follows the curvature of the earth. This allows to have a constant tunnel depth, while for a 50km long laser straight tunnel, the central region would have an additional depth of 50m.

In this paper we assume that following the equipotential of the earth gravitational potential and following the terrain is similar, which is the case in a level site. We investigate the implications that a terrain following tunnel would have for the main and drive beam in the CLIC main linac.

## MAIN BEAM

In this section we will discuss the impact of a curved tunnel on the preservation of the main beam quality. First we will address the case with no imperfections, then we will discuss the situation with static imperfections and finally we will discuss dynamic imperfections. All the simulations have been carried out with PLACET[2]. The curved linac is simulated using geometry changes elements. In order to guide the beam along the beamline, the quadrupoles were are transversely such that the beam experiences a deflecting kick.

### *Impact on the lattice*

The main parameters of the CLIC main beam are taken from [5]. The transverse emittances are very small in particular in the vertical plane; the preservation of this small value is the most important design goal. The beam line consists of a sequence of FODO cells with a length that increases along the linac while the phase advance per cell is constant. The accelerating structures are placed between the quadrupoles. In the curved tunnel, the linac will consist of short straight pieces which extend from one quadrupole to the next. These pieces are connected with small angles that provide the required curvature. The beam is guided to follow the linac by moving the quadrupoles to a transverse position that gives the necessary deflection. In the case of a linac without any imperfections, the beam will be well centered in the accelerating structures. This avoids significant effects of the transverse wakefields.

A problem is caused by the energy spread in the main linac that needs to be large, in the order of a few percent. This is necessary to counteract the strong transverse wakefield effects via the so-called BNS damping. If the main beam had no energy spread, a small jitter of the incoming beam would lead to an enormous emittance growth. The transverse wakefields in each structure would deflect the tail of each bunch to the outside—leading to an ever increasing oscillation amplitude. The BNS damping prevents this effect by introducing an energy spread in the bunches such that the tail has a lower energy. It will consequently be more strongly focused in the quadrupoles than the bunch head. By properly choosing the energy spread, one can ensure that head and tail move with the same amplitude, avoiding the increasing amplitude of the oscillation of the tail. The quadrupoles will bend the beam particles differently depending on their energy, leading to a build-up of dispersion. This can be reduced by carefully choosing the initial dispersion and by correcting the final value.

The emittance growth along the main linac, for the optimum choice of initial dispersion and corrected at the end of the linac, is about $0.4$ nm larger than that for the laser-straight machine. It can be shown that the main contribution arises from the very end of the linac, where the energy

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spread is being reduced. This is due to the fact that in this region the correlation between particle position and energy is more and more lost. By adding dispersion before the end of the linac this the final dispersion corrected emittance can be reduced to about $0.2$ nm.

### *Impact on correction method*

The emittance growth due to static imperfections would be too large to be acceptable in the main linac if one relies on the initial survey only. In order to improve the emittance preservation beam-based alignment is used. The simplest method is to steer the beam through the centers of all the beam position monitors (BPMs) but for CLIC this is not sufficient. An improved method is to not only use the nominal beam but also some additional test beams. As an example one can chose a test beam that is only accelerated with 80% of the nominal gradient. In a laser straight linac one now minimizes the offset of the nominal beam in the BPMs and simultaneously the difference between the trajectories of the test and the nominal beam. This ensures that beam particles with different energies follow the same trajectory; this minimizes the residual dispersion.

In case of the curved linac, the beam needs to have dispersion. One therefore needs to make the two beams take different trajectories, with the difference defined by the design dispersion. If the calibration factor for the BPM response to a beam offset is only known with limited precision the difference between the two trajectories is measured with the same limited precision. Hence an incorrect value of the dispersion is chosen by the correction technique.

In order to produce the energy spread necessary for the test beams, different options are considered: one could vary the RF amplitudes or the phases in the main linac, use the bunch compressor to offset longitudinally the bunches, etc. It is clear that the largest energy spread would be achieved using both electron and positron bunches in the same linac [3]. This option, which is appealing in case of a straight linac, is not feasible in case of a curved one. The reason is that the deflecting kick due to the misalignment of the quadrupoles, which is used to guide the electrons (positrons) around the curvature, would give to the test positron (electron) bunches a kick in the *opposite* direction (because of their opposite charge), making this method fruitless.

Dispersion free steering is followed by an optimization of emittance tuning bumps. In a number of places in the main linac accelerating structures are moved transversely in order to maximize the overlap of the beam with a laser wire at the end of the linac. Details of the method can be found in [1]. In addition to these wakefield bumps a dispersion bump is used before and after the main linac in order to minimize dispersion effects.

We simulate the beam-based alignment and the bump optimization using PLACET [2] with the reference tolerances for CLIC. The BPM calibration errors have been parameterized by a simple error in the scale, i.e. $x_{meas} = ax_{real}$, where $a$ has a Gaussian distribution around 1. The results can be found in Fig. 1. In the case of perfectly calibrated BPMs no difference is observed between the laser straight and the curved machine. In case of a scale error in the BPM response, the full performance can be recovered in the laser-straight linac by iterating the procedure. In case of the curved linac a residual emittance growth remains; for a 2% scale error the additional effect is small, for 5% it quite noticeable and for 10% scale error the emittance it contributes as much emittance growth as all other effects together. If the BPMs cannot be calibrated *in situ* scale errors of up to 20% might be expected [6].

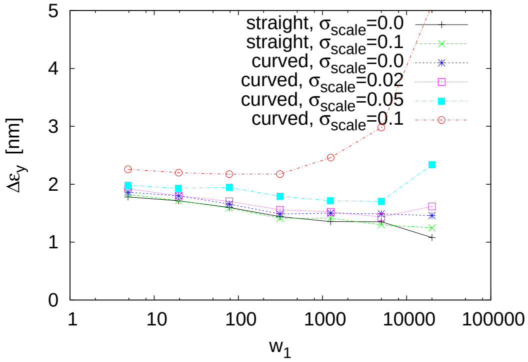

Figure 1: The emittance growth as a function of the correction weight.

### *Dynamic effects*

In order to guide the beam around the curvature the quadrupoles need to be moved transversely such that the beam experiences a deflecting kick. If the strength of the quadrupole is varying the strength of the deflecting kick is varying in the same way. Power supply ripples will thus lead to small transverse deflections of the beam with respect to the design orbit. Since in CLIC no intra-pulse orbit feedback can be used, the relative quantity is the multi-pulse emittance, the emittance integrated over a few consecutive pulses. We simulated this emittance as a function of the RMS variations of the quadrupole strength in a perfect machine, see Fig. 2. Even a tight power supply stability of $3 \times 10^{-5}$ leads to about 4% emittance growth. While this might be manageable both in in terms of the power supply stability as in terms of emittance growth, it is certainly not desirable.

The whole linac RF is produced by drive beam pulses that are produced in the same complex. Hence RF phase and amplitude errors that are constant along the whole main linac have to be expected. We simulated these errors for the perfect machine. The acceptable level of gradient jitter is defined by the acceptable error in the final beam energy in the laser straight machine, which is $10^{-3}$. The multi-pulse emittance growth associated with this gradient jitter is found to be within the simulation noise. Due to the required energy precision, the RF phase jitter needs to

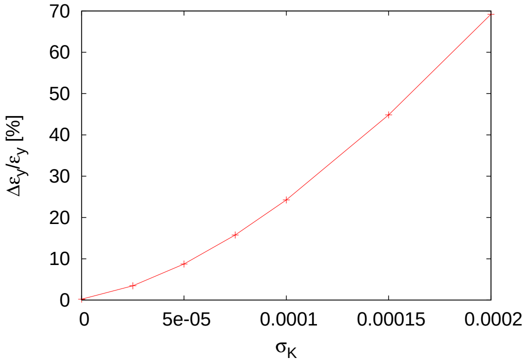

Figure 2: The emittance growth as a function of the strength jitter of the quadrupoles.

be limited to less than about $0.25°$. The resulting emittance growth in the perfect curved linac is about $2\%$, this is more than the growth obtained in a realistic laser-straight linac [4].

### *Failure Modes*

Studies of failures modes in the CLIC main linac have been started. Effects of a jitter in the accelerating phase have been considered in case of curved and straight linacs, for perfectly aligned machines. Phase jitters in the range $[0, 90]$ degrees have been introduced to study their impact in terms of beam loss. Simulations showed that there is not beam loss for phase errors below 36 degrees and that, for greater errors, curved and straight layouts behave rather similarly. These results, as well as more realistic cases including misalignments of the machine, are in progress.

## DRIVE BEAM

The RF power that accelerates the main beam is generated by decelerating a high-current low-energy drive beam in decelerators that run in parallel with the main linac. The length of each of the 22 decelerators per linac is about 600 m. Each of them consist of a FODO lattice with a quadrupole spacing of about 1.1 m. Between each quadrupole pair one power extraction and transfer structure (PETS) is placed. Different options for the design of these structures exist; an optimization is ongoing. For the current study we picked a particular design [7] but the conclusions are not expected to depend on the particular choice.

During the drive beam passage the beam particles loose energy, up to 90% of the initial value. Since some particles—at the beginning of the train—do not loose any energy, the resulting energy spread can be as big as a factor of ten.

Two options exist to adjust the layout of the drive beam decelerator to the tunnel curvature. One can introduce a small angle between each pair of support modules or one could make the straight sections as long as in the main linac. The latter solution follows more closely the main linac but will yield somewhat worse results. Figure 3 shows the envelope of a drive beam in a laser straight decelerator and in two curved ones. If an angle is introduced between all modules no difference is found between laser straight and curved, if the angle is introduced only every eighth modules—eight times larger in this case—the effect is visible but still very small. One can conclude that one should not expect a major problem in preserving the quality of the drive beam in the curved tunnel.

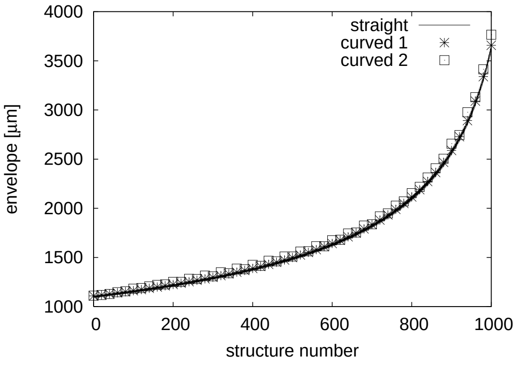

Figure 3: The 3-$\sigma$ envelope of the drive beam in a laser straight and curved linac. In case 1, a small angle is introduced between each pair of modules, in case 2 only every eight modules.

## CONCLUSIONS

The possibility has been investigated to use a tunnel that follows the curvature of the equipotential of gravity. Such a solution would make the preservation of the beam quality more challenging. An important difference between laser straight and curved main linac is the importance of BPM scale errors for the beam-based alignment: in the straight machine this error can be mitigated by integrating a correction, whereas in the curved machine a residual remains. A scale error below 2% is required to suppress this effect to a negligible level. In the curved tunnel the tolerances for the quadrupole power supply stability would be quite tight (in the order of $3 \times 10^{-5}$) as a consequence. Hence the emittance preservation in the curved machine is significantly more challenging than in the laser straight one, but until now we did not find an unsurmountable obstacle.

## REFERENCES

[1] P. Eliasson, D Schulte. CERN-AB-2005-046 (2005).
[2] D. Schulte et al. CERN/PS 2001-028 (AE) and PAC 2001.
[3] D. Schulte, PAC 2001.
[4] D. Schulte. CLIC-Note 432 (2000).
[5] H. Braun et.al. CLIC-Note 627 (2005).
[6] M. Ross. Private communication.
[7] I. Syratchev. Private communication.