

STUDY OF AN ILC MAIN LINAC THAT FOLLOWS THE EARTH CURVATURE*

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Abstract

In the base line configuration, the tunnel of the ILC will follow the earth curvature. The emittance growth in a curved main linac has been studied including static and dynamic imperfections. These include effects due to current ripples in the power supplies of the steering coils and the impact of the beam position monitors scale errors.

INTRODUCTION

Recently, the ILC-GDE [1] has been formed to promote the work on the international linear collider (ILC). The first goal is to evaluate the cost of the project before the end of this year. One of the critical issues that can have significant impact on the cost is the question of the tunnel layout. A specific question is whether the tunnel can follow the earth gravitational potential or whether it needs to be laser straight. A discussion of this question can be found in [2]; it concluded that for the cryogenic system it is advantageous to follow the gravitational potential, to allow for a simpler design of the helium distribution system. For the cost of the civil engineering, the conclusion is very site dependent. Emittance preservation finally is easiest in the laser straight machine. However, no unsurmountable obstacle had been found that prevented one or the other solution so the recommendation has been to realise the cheapest option, which in many potential sites is likely to be the curved linac.

In this paper we will show details of the beam dynamics studies that are relevant to demonstrate that the emittance preservation appears feasible in the curved linac. First the perfect machine will be analysed then the performance of the beam-based alignment and tuning procedures. Finally the beam jitter due to the corrector coils is considered.

LATTICE DESIGN

We focus on a lattice design in which each cryomodule contains eight accelerating cavities and each third module also contains a quadrupoles in the centre. The basic conclusion on the feasibility of the curved linac should also be valid for somewhat longer quadrupole spacing.

The main linac lattice is the same in case of a laser straight or a curved linac. We assume that the cryo modules are straight and that a small angle is introduced between each pair of modules to follow the earth curvature. The beam will be steered to follow the beam line using

the corrector coils that are integrated into each quadrupole. This will generate dispersion in the linac, which can impact the emittance preservation. We add dispersion to the beam before and remove it after the main linac. The values are adjusted as to minimise the final projected emittance at the end of the linac. For a perfect linac it is indeed found that the difference in emittance growth between the laser-straight and curved tunnel is negligible.

BEAM-BASED ALIGNMENT PROCEDURE

In order to ensure emittance preservation beam-based alignment is required in the main linac. We chose dispersion steering as the alignment method. The beam line is split into a number of overlapping bins each of which contains 40 quadrupoles. Each bin starts 20 quadrupoles after the first quadrupole of the previous bin. The bins are corrected one after the other starting at the beginning of the linac using the nominal beam and a test beam. The test beam has an energy different from the nominal one. In case of a laser straight machine one aims to minimise the following figure of merit

$$M = \sum_i w_0 y_{0,i}^2 + \sum_i w_1 (y_{0,i} - y_{1,i})^2 \quad (1)$$

Here, $y_{0,i}$ are the offsets of the nominal beam in the BPMs and $y_{1,i}$ are the offsets of the probe beam. The first term limits the trajectory of the nominal beam while the second minimises dispersion by making the trajectories at different energies equal. Typically one uses $w_1 \approx \sigma_{res}^{-2} \gg w_0 \approx \sigma_{BPM}^{-2}$.

In case of a curved linac, the different beams will not follow the same trajectory even for perfect alignment. Hence we modify the figure of merit to account for the target difference of the trajectories Δ_i due to dispersion:

$$M = \sum_i w_0 y_{0,i}^2 + \sum_i w_1 (y_{0,i} - y_{1,i} - \Delta_i)^2 \quad (2)$$

The emittance preservation can be improved by applying tuning bumps after the beam based alignment. These bumps are based on an emittance measurement after the end of the main linac. The dispersion added before and after the main linac is varied in order to optimise the final emittance.

The simulations in the following are performed with PLACET [3], assuming completely static machines. The same alignment errors as for the laser straight machines are considered, see table 1.

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Table 1: Alignment errors assumed in the simulations. The first four are with respect to the cryo module, the last two with respect to the ideal machine.

Error	Symbol	Value
BPM position	σ_{BPM}	200 μm
Quadrupole position	σ_{quad}	300 μm
Cavity position	σ_{cav}	300 μm
Cavity angle	σ_{tilt}	300 μradian
Module position	σ_{mod}	200 μm
Module angle	σ_{angle}	20 μradian

Errors in the BPM calibration can affect the performance of the dispersion steering, since the measured dispersion differs from the actual one in each BPM. In case of a laser-straight linac the impact of such errors can be removed by iterating the correction procedure. One aims to make the dispersion zero so only the small residual value will be incorrectly measured. In case of a curved tunnel one aims to achieve a non-zero target dispersion and hence will be left with a larger error.

In the following we assume that the BPM reading $x_{i,r}$ is linear to the actual offset x_i of the beam from it's centre, but that the slope a_i is only known with limited accuracy

$$x_{i,r} = a_i x_i$$

It is assumed that the scale factors have a Gaussian distribution with a width σ_a around 1 and that these factors do not change with time. Without in-situ calibration the scale error could be as large as 20% [6].

RESULTS

First we consider the case with a BPM resolution of $\sigma_{\text{res}} = 10\mu\text{m}$. The test beam has at any point 80% of the energy of the nominal beam. We iterate the alignment procedure of each bin three times in order to ensure that the method converged. Figure 1 shows the emittance growth as a function of w_1/w_0 for this case. A scale error of 5% leads to a small additional emittance growth; even a scale error of 10% seems to be acceptable.

In the case of a better BPM resolution of $\sigma_{\text{res}} = 1\mu\text{m}$, the relative impact of the scale error is much larger, see Fig. 2. One can conclude that a 10% BPM scale error renders a BPM resolution of better than $\sigma_{\text{res}} \approx 10\mu\text{m}$ useless for the static alignment. The main remaining advantage of the better BPM resolution is that it allows to reduce the energy difference between test and nominal beam.

In order to reduce the scale error induced emittance growth one can try to use in-situ calibration to reduce the size of the error. If the BPMs were mounted on movers this calibration could be easily performed; this is however not the case in ILC. One can also calibrate the BPMs if the corrector coils are well calibrated and the beam energy is well known along the linac. In this case the expected beam

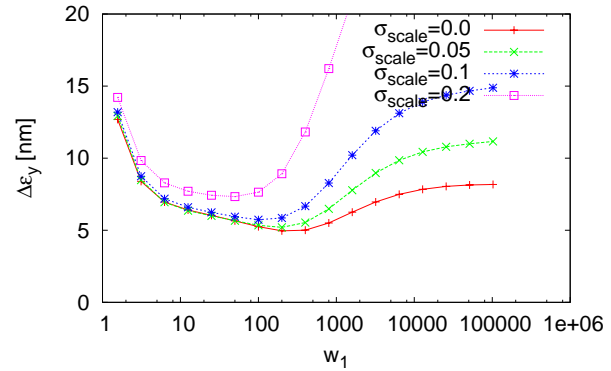


Figure 1: Emittance growth as a function of the weight w_1 ($w_0 = 1$) for different calibration errors σ_a . The test beam has a beam energy 20% below the nominal and the BPM resolution is 10 μm .

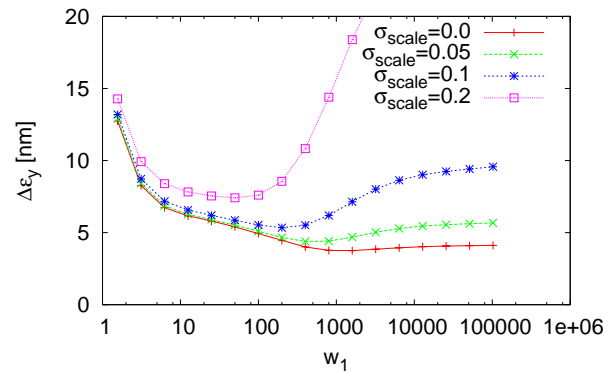


Figure 2: Emittance growth as a function of the weight w_1 for different calibration errors σ_a . The BPM resolution is 1 μm .

motion can be compared to the measured one. It is also possible to induce betatron oscillations and deduce the scale from them, provided that the lattice is known well enough. However, another solution is to reduce the growth by additional tuning, as is shown in the next section.

IMPACT OF EMITTANCE TUNING BUMPS

Emittance tuning bumps can significantly reduce the emittance growth in ILC [5] and is likely required already in the laser-straight linac. We investigate the impact of one dispersion bump before and one after the main linac. A detailed description of the method can be found in [5].

The dispersion tuning bumps indeed significantly reduce the emittance growth, see Fig. 3. The result for the curved linac with zero BPM scale error is almost identical to that for the laser straight machine. For larger scale errors the curvature however does not allow to use large values of w_1 and thus deprives us from taking full advantage of the good BPM resolution.

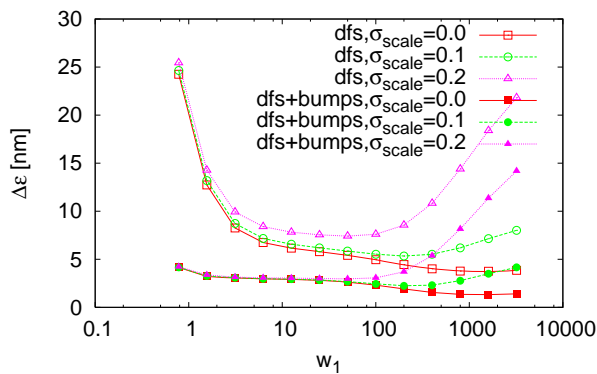


Figure 3: Emittance growth as a function of the corrector weight, if dispersion tuning bumps are used. A BPM resolution of $1 \mu\text{m}$ is considered.

DYNAMIC EFFECTS

The beam will be guided around the curvature by using the corrector coils in the quadrupoles. Small variations of the strength of these correctors can arise from ripples of the power supply and lead to deflections of the beam with respect to the nominal trajectory. We are focusing on the additional effect due to the earth curvature, hence we study this effect for a perfectly aligned linac. An additional effect is expected from the initial misalignments but this is expected to be the same for a curved and a laser straight linac. We simulate the single- and multi-pulse emittance growth. The former is relevant if an intra-pulse feedback corrects the beam trajectory at the end of the linac and full luminosity optimisation is performed at the interaction point. The latter is the emittance integrating over a few pulses and assuming that no feedback is used. The main contribution is due to the trajectory jitter, hence 12% growth corresponds to a jitter of 0.5σ .

While the found emittance growth is small—see Fig. 4—one should be aware that the emittance is a relevant measure of the luminosity only if the beam-beam offset and angle are optimised for luminosity [7]. Otherwise the luminosity loss can be enhanced by the beam-beam effects [8]. The required stability of a few times 10^{-4} is well within the state of the art.

BENCHMARKING

In order to benchmark the PLACET results the simulation of the curved linac has also been performed with MERLIN [4] for a weight $w_1 = 1600$. In this case no tuning bumps have been used but the plotted emittance is dispersion corrected. As can be seen in Fig. 5 the agreement between MERLIN and PLACET is quite good.

CONCLUSION

We have studied the impact of a curved tunnel on the emittance preservation in the main linac of ILC. In principle the same performance can be reached in both cases

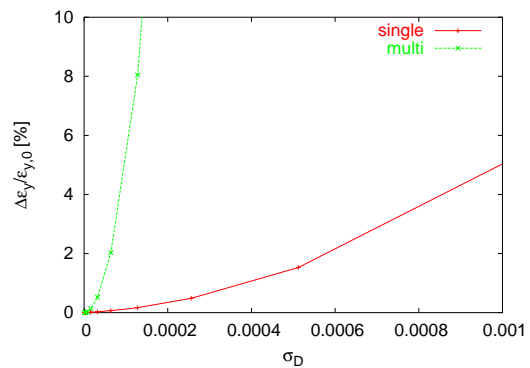


Figure 4: Emittance growth as a function of the dipole corrector power supply ripples σ_D . A perfectly aligned linac is assumed and the single-pulse as well as multi-pulse emittance growth are shown.

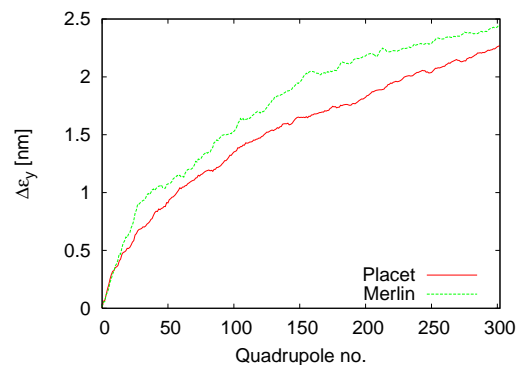


Figure 5: Emittance along the linac comparing MERLIN and PLACET results.

except that BPM calibration errors can significantly impact the performance of the beam-based alignment algorithm in the curved linac. Scale errors above 10% are significantly impacting the emittance growth. Dispersion tuning bumps can significantly reduce the emittance growth so that even scale errors as high as 20% seem tolerable. But still smaller values are strongly desired in order to take full advantage of BPM resolutions in the order of $1 \mu\text{m}$. The required power supply stability for the corrector coils has also been studied and found to be not critical.

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