SIMULATION STUDY OF SCALE ERROR EFFECT OF BPM IN ILC MAIN LINAC CORRECTIONS

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Abstract

For preserving low emittance beam in the ILC (International Linear Collider) main linacs, DMS (Dispersion Matching Steering) is planed to be used as a main correction method. The linacs are following the earth's curvature and the designed vertical dispersion in the linacs can not be zero. For this reason, the orbit difference due to beam energy difference will have to be measured accurately and tolerance of scale error of beam position monitors (BPM) can be tight. Here, the tolerance of the scale error is estimated by tracking simulations and optics design for relaxing the tolerance is reported.

ILC MAIN LINAC FOLLOWING EARTH CURVATURE

The main linac of ILC is designed to be curved, following the earth's curvature. This makes the supply system of liquid helium for cooling the accelerating cavities simpler and less expensive [1].

Beam line components relevant to beam dynamics are accelerating cavities, quadrupole magnets, steering magnets and beam position monitors. Every quadrupole magnet has a steering magnet and a BPM (beam position monitor) attached closely, making a "magnet-BPM package". All beam line components are aligned to the vertically curved line, following the earth's curvature.

In the original beam optics, beam is designed to go through centers of all the quadrupole magnets using steering magnets. Since the beam goes straight between magnets, the designed beam orbit has small displacement from the designed alignment line, which is shown in Figure 1 as "RDR optics" (RDR: Reference Design Report [1]). Figure 2 shows the vertical dispersion, which is not zero due to the curvature. The displacement excites wakefield in cavities, but it was shown that the effect of this small displacement is not significant.

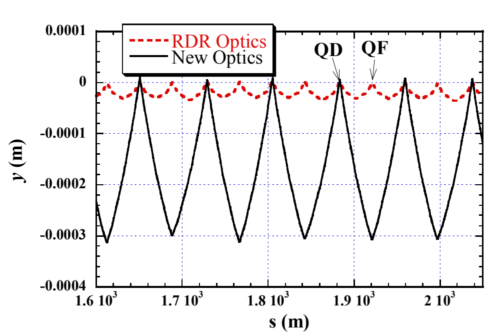

Figure 1: Designed vertical beam orbit distortion from the designed alignment line. Dotted red line is for the original (RDR) design and solid black line for the new design. QD and QF indicate locations of vertically de-focusing and focusing quadrupole magnets, respectively.

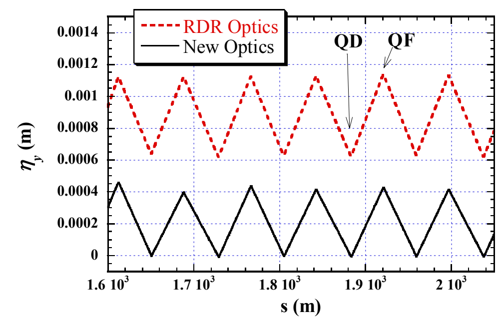

Figure 2: Designed vertical dispersion. Dotted red line is for the original (RDR) design and solid black line for the new design. QD and QF indicate locations of vertically de-focusing and focusing quadrupole magnets, respectively.

DISPERSION MATCHING STEERING

Designed vertical emittance is much smaller than horizontal emittance and preserving vertical emittance is critically important for ILC (designed normalized emittance at the entrance of the linac is about 20 nm in vertical and about 8 μm in horizontal). There are two major reasons of the vertical emittance growth in the main linac, vertical dispersion and x-y coupling. Vertical dispersion is induced by non-designed vertical kicks, the main sources of which are offset misalignment of quadrupole magnets and vertical tilting (rotation around horizontal axis) of accelerating cavities. For reducing the emittance growth, the DMS (Dispersion Matching Steering) technique is planning to be used. In this technique, beam orbits are measured with different beam energies, different setting of accelerating voltages. Then, setting of steering magnets are calculated to minimize

$$w\sum_i (y_{2,i} - y_{1,i} - \Delta y_{\mathrm{design},i})^2 + \sum_i (y_{1,i} - y_{\mathrm{design},i})^2 , \quad (1)$$

where i is index for BPM, $y_{1,i}$ is the measured vertical beam position at the i-th BPM with nominal beam energy (nominal beam), $y_{2,i}$ the measured vertical beam position with different beam energy (test beam), $y_{\mathrm{design},i}$ the designed vertical beam position with the nominal beam energy, $\Delta y_{\mathrm{design},i}$ the designed vertical beam position difference of the two different beam energies. In the case the ratio of the beam energies of two settings is constant ($\delta = (E_2 - E_1)/E_1$) along the linac, we may write $\Delta y_{\text{design},i}$ as

$$\Delta y_{\text{design},i} = \delta \eta_{\text{design},i}\,, \quad (2)$$

where $\eta_{\text{design},i}$ is the designed dispersion at i -th BPM.

For a straight beam line, $y_{\text{design},i}$ and $\Delta y_{\text{design},i}$ will be zero everywhere. However, for a curved linac, such as the ILC main linac, they cannot be always zero.

Minimizing the first term makes the dispersion distortion small and minimizing the second term makes the orbit distortion small. w is a factor for controlling the relative weights of two terms. The first term, a sum of difference of measurement is affected by BPM resolution and the second term is affected by BPM offset misalignment and BPM resolution. BPM resolution is expected to be much smaller than typical BPM misalignment. Then, roughly, $\sqrt{w}$ should be set to be ratio of typical BPM misalignment and BPM resolution divided by $\sqrt{2}$, if we ignore scale error of BPM, which is considered later. Typical residual dispersion error at each BPM will be comparable to the BPM resolution times $\sqrt{2}$ divided by the relative beam energy change of the test beam, which is about 14 µm, assuming BPM resolution 1 µm and beam energy change of 10% ($\delta = -0.1$).

The red circles of Figure 3 shows result of tracking simulations, expected emittance growth in the ILC main linac (average from 40 random seeds) as a function of the weight factor w . Simulation code SLEPT [2] is used. Misalignment and errors were set randomly with rms as in the table 1 and $\delta = -0.1$ is set for DMS.

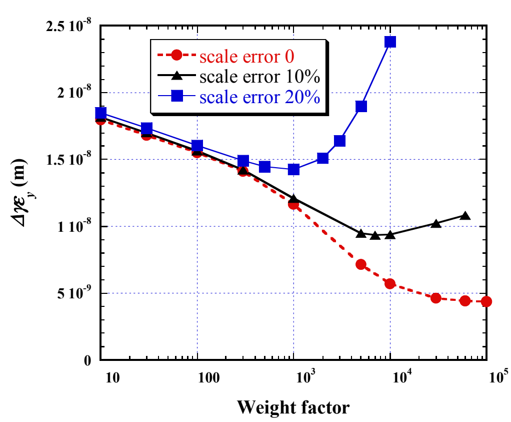

Figure 3: Expected emittance growth, average from 40 random seeds, as a function of the weight factor. For the original optics design, with three different scale errors, Red circles: No scale error, black triangles: RMS 10%, and blue rectangulars: RMS 20%.

The optimum weight factor w is expected to be square of the ratio of typical BPM misalignment and typical BPM resolution, divided by 2,

$$w_{\text{optimum}} \approx (360/1)^2/2 \approx 60000\,, \quad (3)$$

which is consistent with the simulation.

Table 1: RMS of Errors in simulations

Quadrupole magnet vertical offset	0.36 mm
Quadrupole magnet rotation	0.3 mrad
Acc. Cavity vertical offset	0.64 mm
BPM vertical offset	0.36 mm
BPM resolution	1 µm

EFFECT OF BPM SCALE ERROR

It was realized that accurate calibration of the scale of BPM reading is not easy and reasonable assumption of the scale error is about 10% to 20% [3]. The scale error affects the first term of eq. (1) significantly for ILC main linacs. The apparent position difference at i -th BPM is adjusted to $\Delta y_{\text{design},i}$, which means the real position difference is adjusted to $(1+\kappa_i)\Delta y_{\text{design},i}$, where κ_i is the scale error of i -th BPM. Contribution of the scale error to typical residual dispersion error at each BPM will be typical $|\kappa_i \Delta y_{\text{design},i}|$ divided by the relative beam energy change of the test beam, which is

$$\left|\kappa_i \Delta y_{\text{design},i}/\delta\right| \approx \left|\kappa_i \eta_{\text{design},i}\right| \quad (4)$$

and it is about 70~110 µm, assuming $\kappa_i \approx 0.1$ and from the dispersion shown in Figure 2. This is about 5~8 times larger than the expected contribution of BPM resolution.

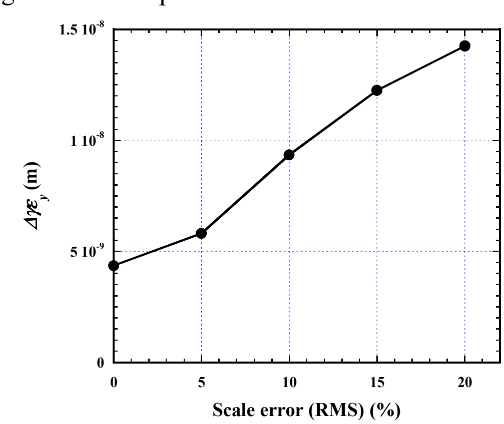

Figure 4: Expected emittance growth, average from 40 random seeds, as a function of RMS of the BPM scale error for the original optics.

Figure 3 shows result of tracking simulation, expected emittance growth in the ILC main linac (average from 40 random seeds) as a function of the weight factor w , with BPM scale error 0, 10% and 20%. Other errors are the same as described in the previous section. As expected, the optimum weight factor is small for large scale error. Figure 4 shows expected emittance as function of BPM scale error, choosing the optimum weight factor for each scale error.

It has been shown that the BPM scale error of 10% causes significant emittance growth (additional $\Delta\gamma\varepsilon_y \approx 5\,\text{nm}$), and will not be acceptable. However, it will not be easy to make the scale error smaller. In the next section, a new optics for mitigating the scale error effects will be discussed.

NEW OPTICS MITIGATING EFFECT OF BPM SCALE ERROR

The significant effect of the BPM scale error comes from large designed vertical dispersion. Though it is impossible to make dispersion zero everywhere in the curved linac, it is possible to make the dispersion smaller. One example was tested by simulations. The newly designed vertical orbit (deviation from the curved alignment line) and the vertical dispersion are shown in Figures 1and 2. Dispersion is reduced and set to be almost zero at every vertically de-focusing quadrupole magnet. Design orbit goes through centre of every de-focusing quadrupole magnet but has offset at focusing magnets. It should be noted that, for this new optics, all hardware components do not need to move from the original optics, strengths of all quadrupole magnets are the same as the original optics (beta-function is the same everywhere). Only strengths of steering magnets and injection beam condition (orbit and dispersion) have to be slightly modified. So, in actual operation, both the original and this new optics can be tested without any major changes.

The orbit from the curved alignment line becomes larger as shown in Figure 1, but it will not induce significant emittance growth, as shown later.

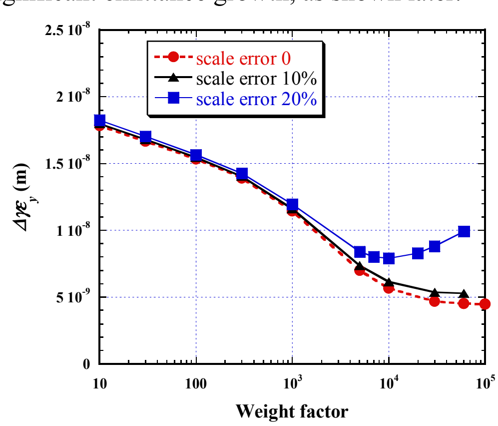

Figure 5: Expected emittance growth, average from 40 random seeds, as a function of the weight factor. For the new optics design with three different scale errors, Red circles: No scale error, black triangles: RMS 10%, and blue rectangulars: RMS 20%.

The new optics is expected to mitigate the effects of the BPM scale error in DMS, because of the small designed dispersion. Following the same consideration for the original optics, typical residual dispersion error with the new optics will be about 0~40 micron, assuming 10% BPM scale error, much smaller than that for the original optics.

Figure 5 shows result of tracking simulation, expected emittance growth in the new optics (average from 40 random seeds) as a function of the weight factor w, with BPM scale error 0, 10% and 20%. And Figure 6 shows expected emittance as function of BPM scale error, choosing the optimum weight factor for each scale error.

Comparing these figures with those for the original optics, it is clear that the new optics is much less sensitive to the BPM scale error. The scale error 10% (RMS) is expected to increase only 1 nm growth of the normalized emittance, 5 times smaller than for the original optics.

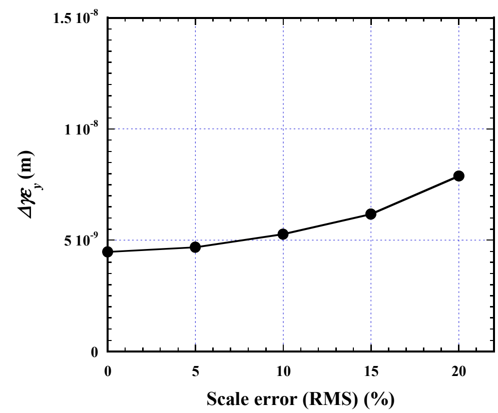

Figure 6: Expected emittance growth, average from 40 random seeds, as a function of RMS of the BPM scale error for the new optics.

SUMMARY AND DISCUSSIONS

The scale error of BPM will cause significant emittance growth in the vertically curved ILC main linacs, in the originally designed optics. The correction method DMS is affected by the scale error with large designed vertical dispersion along the linacs.

A new optics design with smaller vertical dispersion is proposed for mitigating the effects of the scale error. The change is minor, only strengths of steering magnets and injection beam condition (orbit and dispersion) have to be slightly modified.

Simulations have shown the scale error 10% (RMS) is expected to increase the normalized emittance by 5 nm in the original optics and only 1 nm in the new optics.

REFERENCES

[1] ILC Reference Design Report, http://www.linearcollider.org/about/Publications/Reference-Design-Report

[2] SLEPT is a tracking simulation code for high energy licacs, especially for main linacs of linear colliders, http://lcdev.kek.jp/~kkubo/reports/MainLinac-simulation/SLEPT/SLEPT-index.html

[3] M. Wendt, private communication