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Linac, Beam Dynamics

Beam Dynamics in Curved ILC Main Linacs
(following the earth curvature)

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Design and simulation of curved ILC Main Linac
(for beam dynamics study)

- All Quad-magnets are aligned along the earth curvature, and accelerating cavities are aligned along the straight lines between quads.
- Optics is FODO as shown in Fig. 1.
- In the simulation, thin (zero-length) steering magnet is inserted at the middle of each quad.
- Strength of steering magnets are set to (almost) eliminate beam offset and dispersion at center of every vertically defocusing quad. SAD was used for the calculations. The “Design” orbit and dispersion calculated by SAD are shown in Fig.2a and Fig.2b.
- Particle tracking with this designed linac (no error) was done using SAD. Initial vertical emittance, $\varepsilon\gamma$ 0=2E-8 m and initial energy spread 2.8%. No wakefield was included. Fig. 3 shows vertical projected emittance along the linac. Emittance increase is very small (0.5%).
- As comparison, the same calculations and tracking were done for simply curved orbit, where the beam orbit goes through the centers of all quads. The results are shown in Fig. 4. It has large dispersion and 55% emittance increase.
- Simulation using SLEPT with the designed linac was done, where wakefield was included. Fig. 5 shows vertical projected emittance along the linac. Emittance dilution is very small. The projected emittance is large in the matching section, probably due to slight difference of tracking between SAD and SLEPT (The optics was designed using SAD). But the final emittance was still small (5%).
- Simulation using SLEPT including alignment errors and orbit correction was done, as explained later. The results were compared with simulation of a laser straight linac. There was no significant difference. See Fig. 6.

Design and simulation of curved ILC Main Linac
(for beam dynamics study) (continued)

- Effects of magnet strength fluctuation were also checked briefly. Vertical beam position and angle changes were calculated using SAD, due to magnet strength errors. Fig 7a shows change of position and angle from 100 random seeds, with relative magnet strength error 0.01% (sigma). Fig.7b shows the position change of the same data. Here, relative error of a quad and steering magnet at its middle was set to be the same. Errors of magnets at different locations were independent.
- Random strength error of 0.01% will be too large, by factor about 4, to keep the average beam offset less than 0.14 σ.
- It was found that if all the magnets have the same relative error (systematic error), the effects was much smaller. (Position change is about 3 order less than that in the case of random error.)
- Fig. 8 shows distribution of emittance increase due to magnet strength error 0.1% (sigma) simulated using SLEPT. To make the average of $\Delta\varepsilon/\varepsilon_0$ less than 0.063, the strength error should be less than 0.17%.

Reference: "Following Earth Curvature", talk by N.Walker, in 2nd ILC Workshop, Snowmass, 2005,
http://alcpg2005.colorado.edu:8080/alcpg2005/program/accelerator/WG1/nicholas_walker20050906014642.pdf

Fig. 1, Optics:

FODO

Beam energy: From 5 GeV to 250 GeV

Acc. cavity: 35 MV/m, 10 cavities/module

from 5 GeV to 125 GeV: 2 modules/quad

from 125GeV to 250 GeV: 3 modules/quad

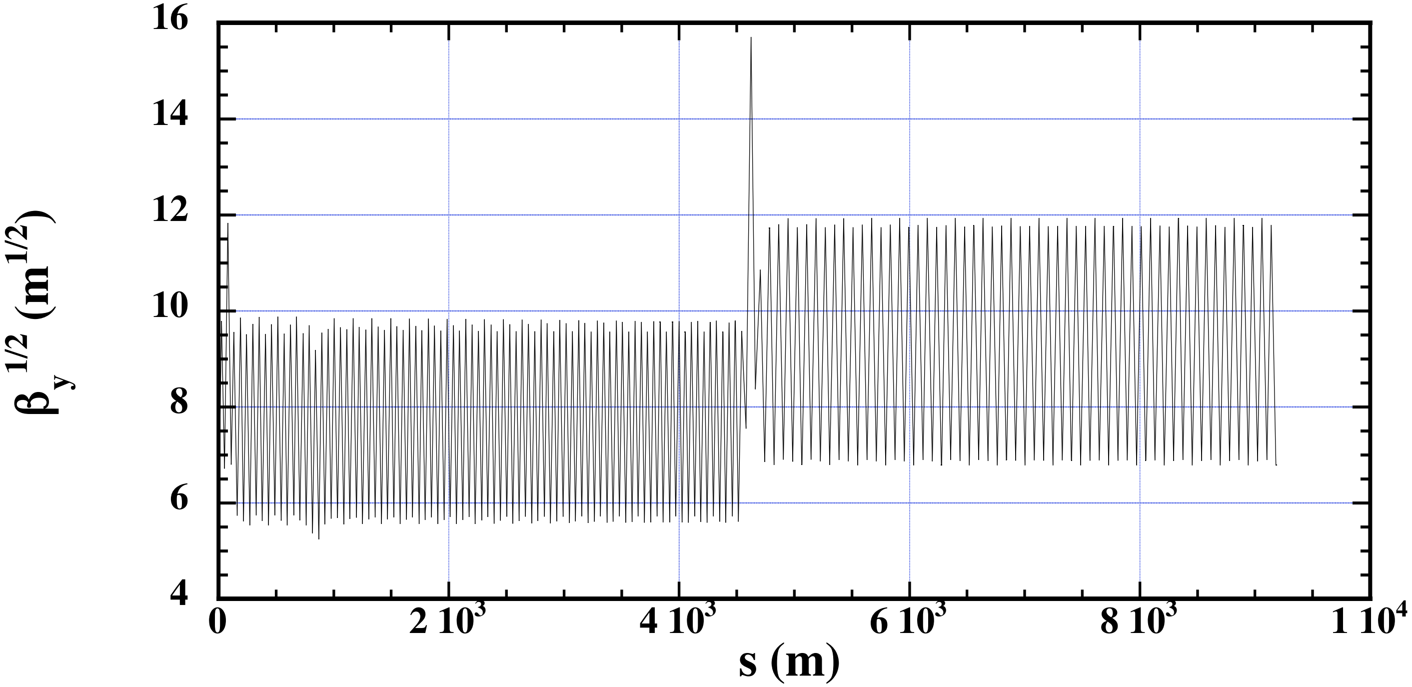


Fig. 2a, “Design” orbit and dispersion calculated by SAD.

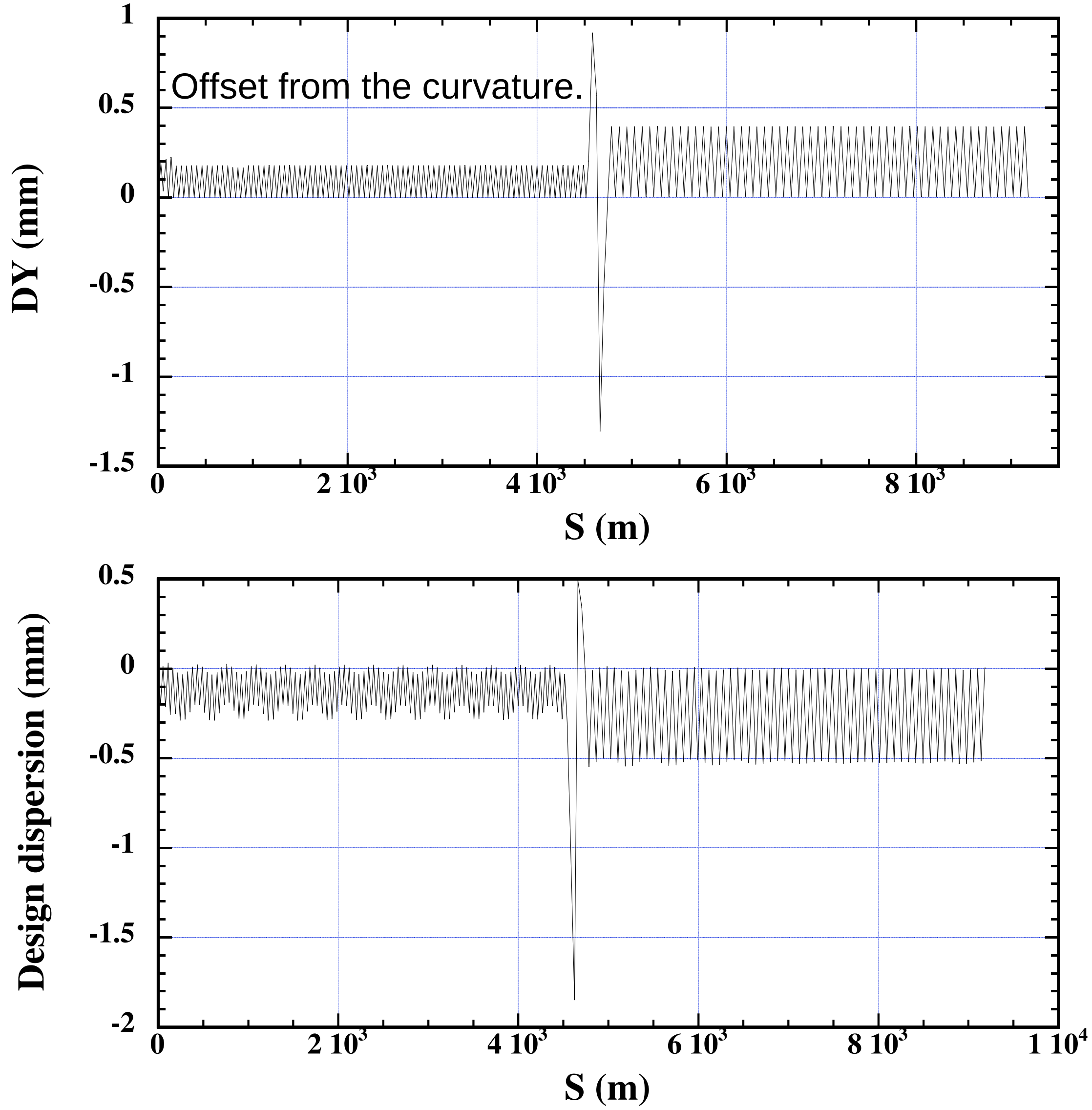
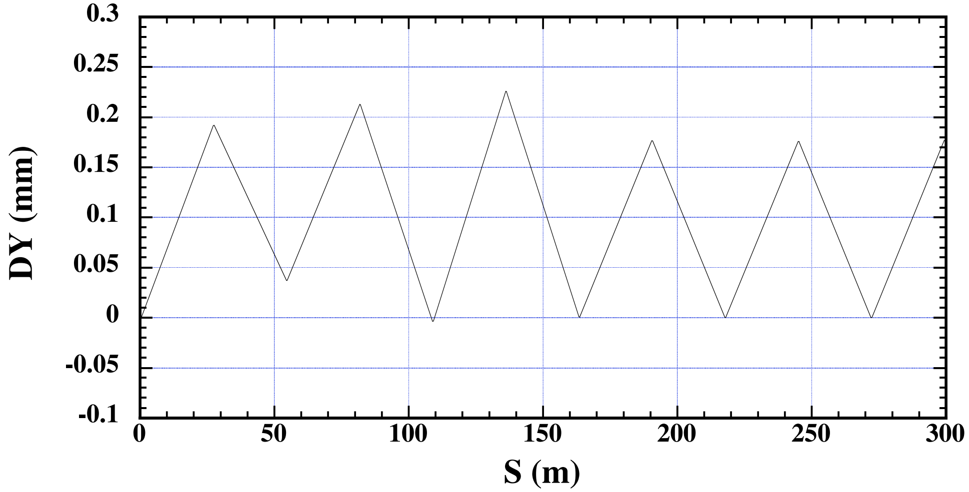
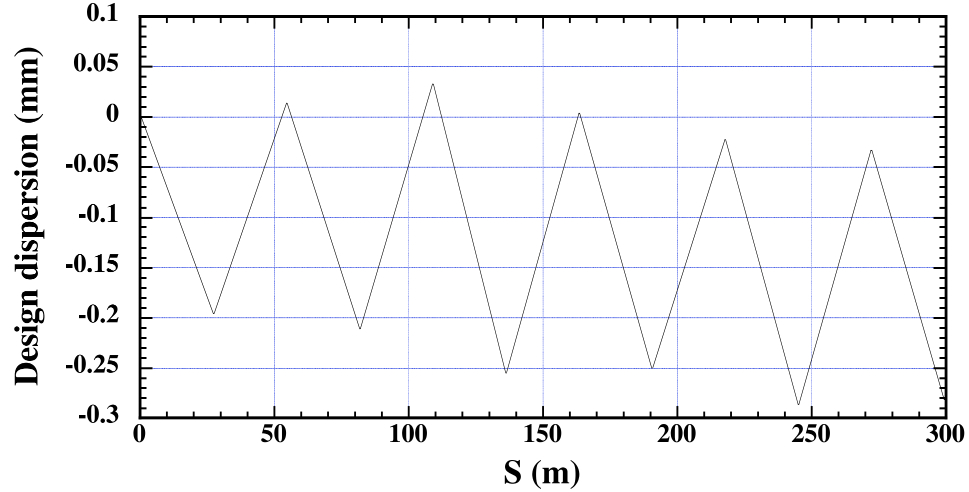


Fig. 2b, “Design” orbit and dispersion near the beginning of linac.

Offset from the curvature.



Dispersion



The curvature and design orbit.

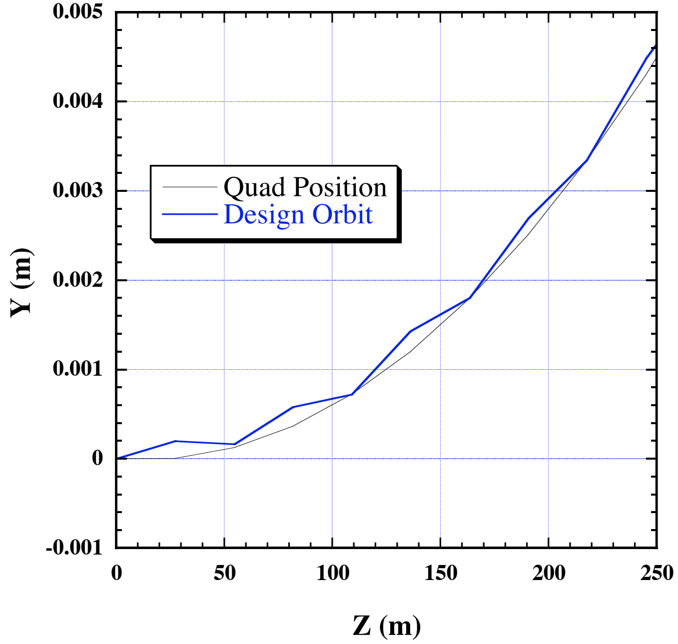


Fig. 3, Result of particle tracking without errors, using SAD.
Projected emittance along the linac.

Initial vertical emittance: εγ0=2E-8 m,

Initial energy spread: 2.8%,

No wakefield.

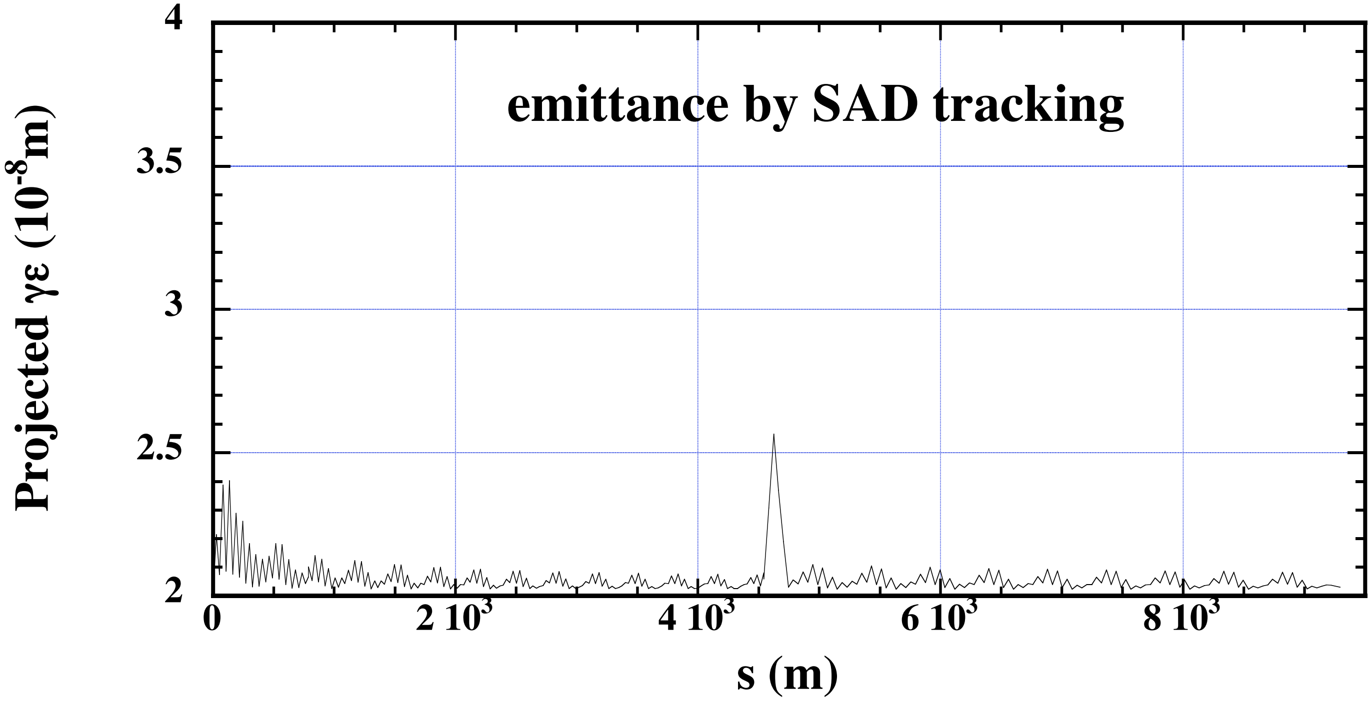


Fig. 4-a,b, Dispersion and projected emittance along a simply curved linac.
Beam orbit is simply curved, going through the center of all quads.

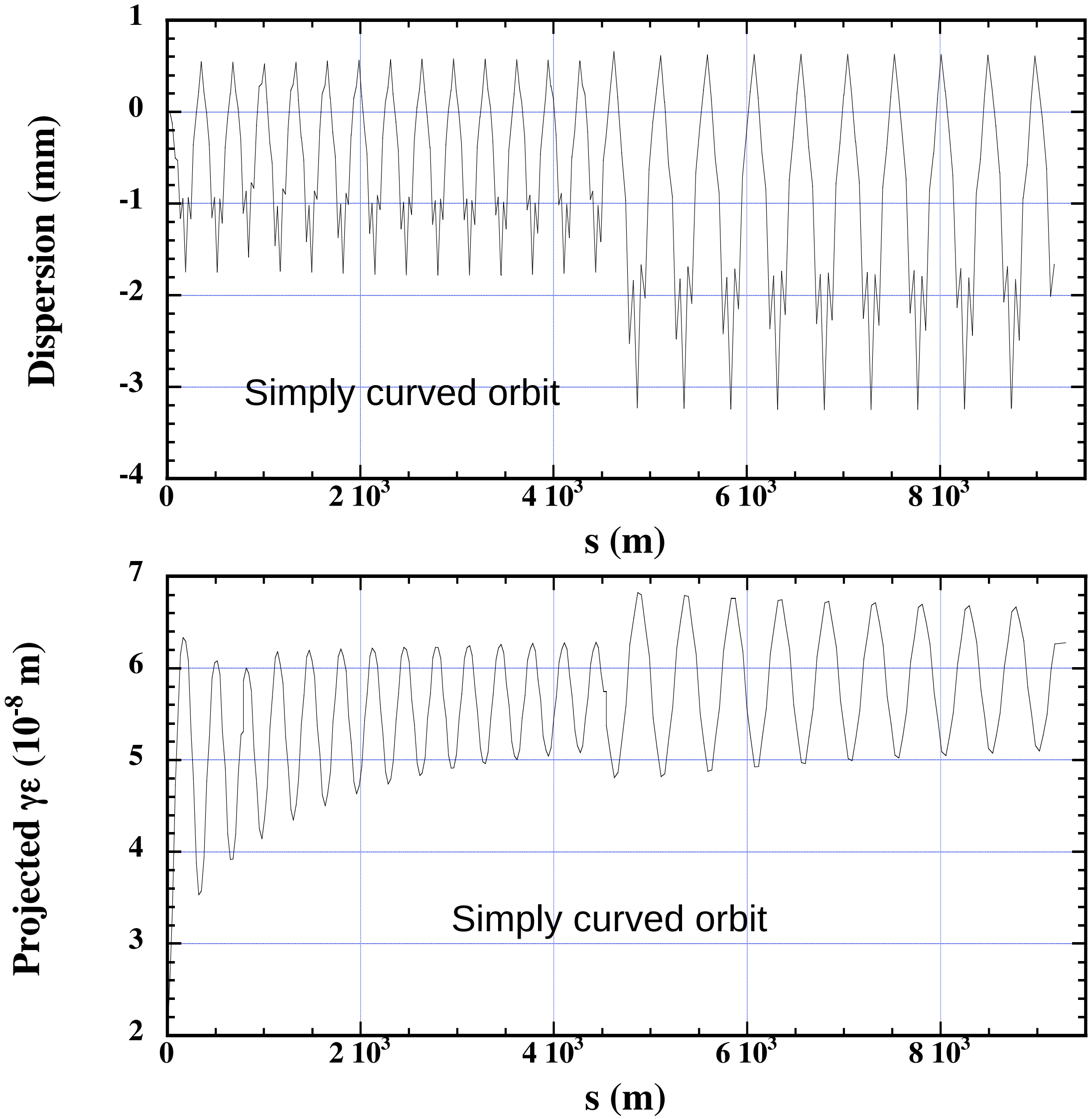
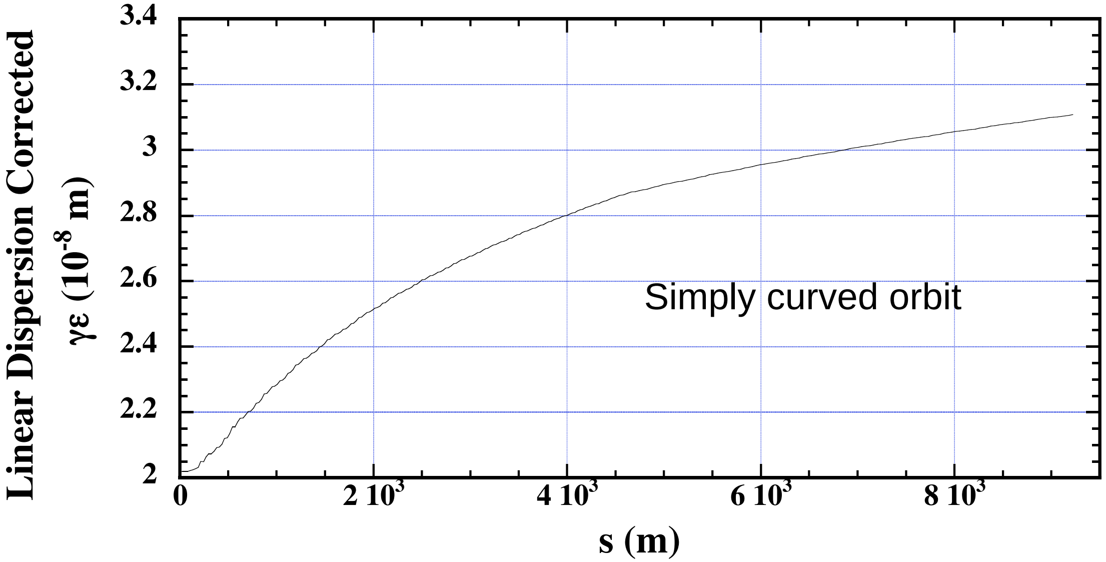


Fig. 4-c, Linear Dispersion Corrected emittance along a simply curved linac.
Beam orbit is simply curved, going through the center of all quads.



Projected emittance

$$\equiv \sqrt{(<y^2> - <y>^2)(<y'^2> - <y'>^2) - (<yy'> - <y><y'>)^2}$$

Linear Dispersion Corrected emittance

$$\equiv \sqrt{(<(y-\eta\delta)^2> - <y-\eta\delta>^2)(<(y'-\eta'\delta)^2> - <y'-\eta'\delta>^2) - (<(y-\eta\delta)(y'-\eta'\delta)> - <y-\eta\delta><y'-\eta'\delta>)^2}$$

y: Vertical offset, y': Verticale angle

δ: Relative energy deviation

$\eta \equiv (<y\delta> - <y><\delta>)/(<\delta^2> - <\delta>^2)$, $\eta' \equiv (<y'\delta> - <y'><\delta>)/(<\delta^2> - <\delta>^2)$

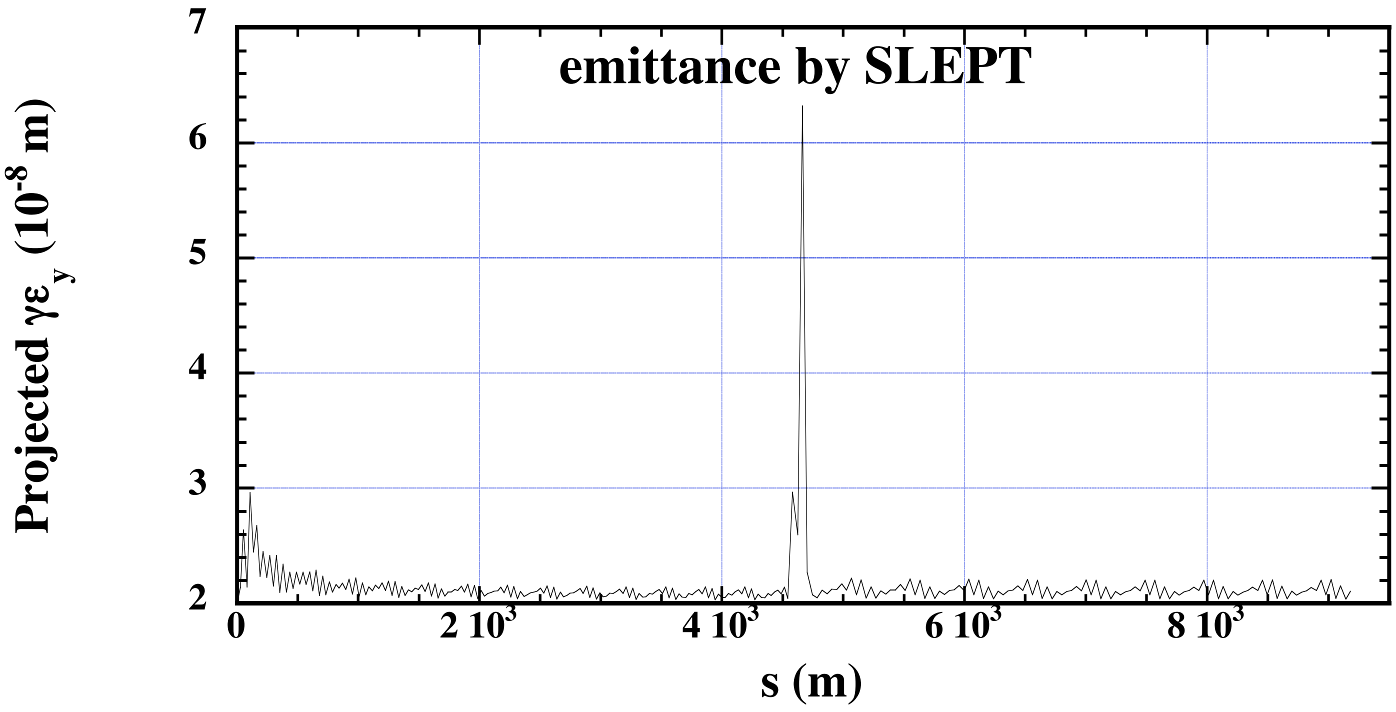
$<>$: Average over all macro-particles

Fig. 5, Result of simulation without errors, using SLEPT.
Projected emittance along the linac.

Initial vertical emittance: εγ0=2E-8 m,

Initial energy spread: 2.8%,

TESLA-TDR wake.



Simulation including alignment errors and orbit correction using SLEPT

Initial normalized vertical emittance:	2E-8 m
Initial energy spread:	2.8%
Random misalignment of quads and cavities:	300 micron
Random unknown offset of BPM with respect to quad:	10 micron
Random error of BPM(resolution):	5 micron

Every quad has a BPM and a steering at its middle.
Correction: Steering correction.

Minimize additional offset and additional kick" at quads.

$$\text{Minimize } r\sum_i y_i^2 + \sum_i \left(\theta_i - k_i y_i\right)^2,$$

θ_i : Additional kick angle (additional to designed kick) of steering at i-th quad

y_i : Offset from designed orbit at i-th quad

k_i : K-value of the i-th quad

r : Weight ratio. $=10^{-3}$

Fig. 6, Results of simulations. Distribution of final projected-normalized emittance.

(Total 100 random seeds in each case.)

(a) Following Earth Curvature

(b) Laser Straight

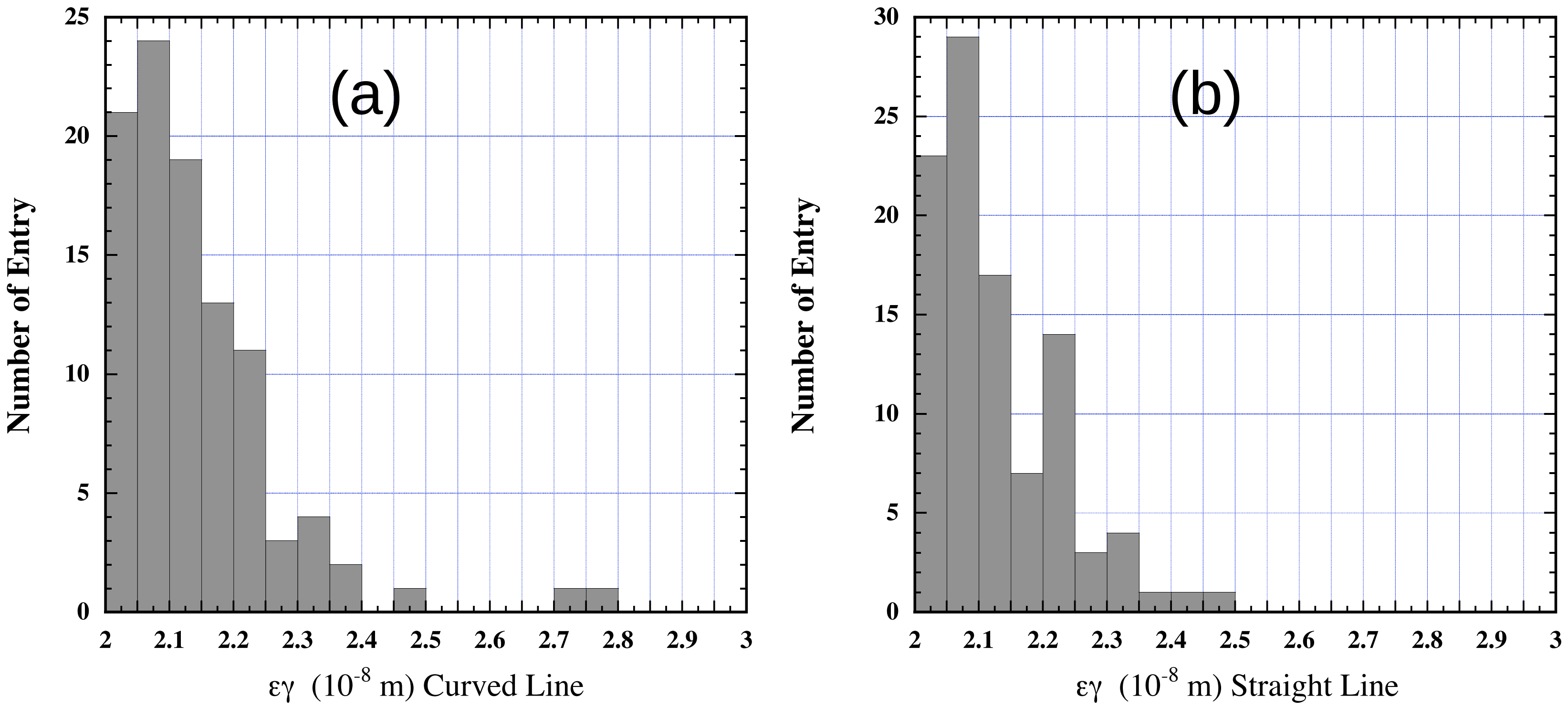
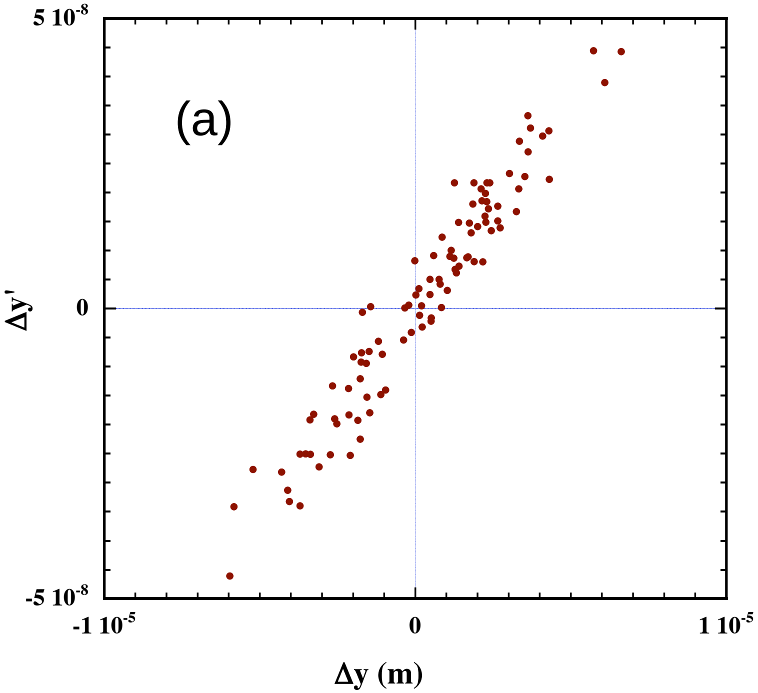


Fig.7, Vertical position and angle change due to magnet strength error.
Calculated by SAD, 100 random seeds.
Relative magnet strength error 0.01% (sigma).
Relative error of a quad and steering magnet at its middle was set to be the same.
Errors of magnets at different locations were set independently.
(a) Position change vs. angle change at the end of linac
(b) Distribution of $\Delta y/\sigma_y$ of the same data.

To make the rms of $\Delta y/\sigma_y$ less than 0.14, the strength error should be less than 0.0025%.
(Random 0.14 σ offset of each beam will make average position offset 0.2 σ between two beams at IP, which will decrease luminosity about 3%, without beam-beam force.)



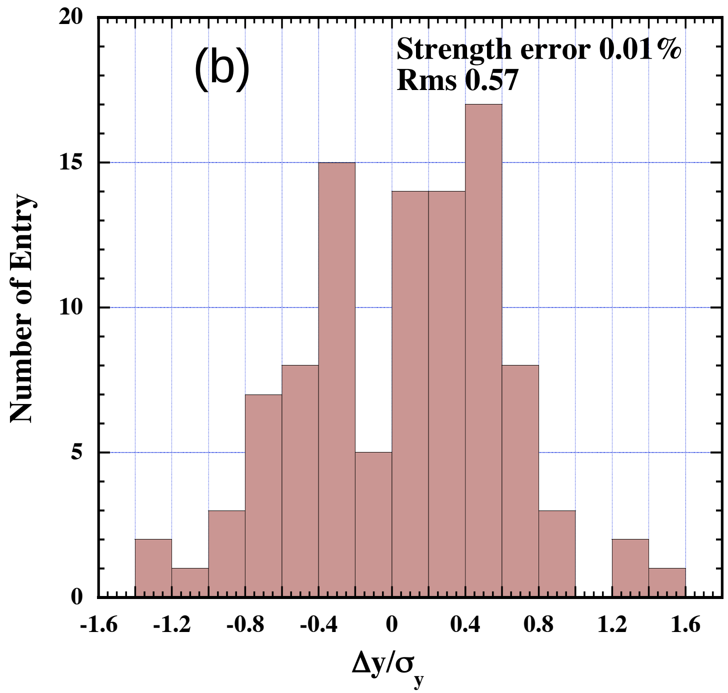
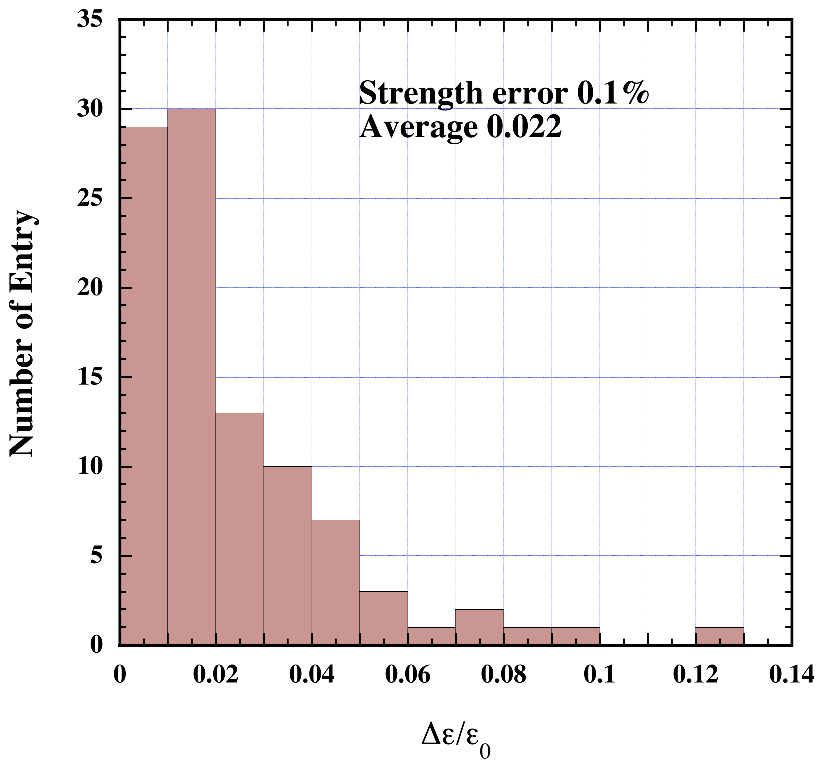


Fig.8, Emittance increase due to magnet strength error.

Simulated by SLEPT, 100 random seeds.
Relative magnet strength error 0.1% (sigma).
Relative error of a quad and steering magnet at its middle was set to be the same.
Errors of magnets at different locations were set independently.

To make the average of $\Delta\varepsilon/\varepsilon_0$ less than 0.063, the strength error should be less than 0.17%.
(Emittance increase by 0.063 will decrease luminosity about 3%, without beam-beam force.)



Summary

- Simulations were done for 250 GeV beam energy linac, assuming all Quad-magnets are aligned along the earth curvature and accelerating cavities are aligned along the straight lines between quads.
- Emittance increase was small without errors.
- Emittance increase with misalignments and orbit correction in the curved linac and the straight linac were almost the same.
- Tolerance of random magnet strength fluctuation (magnet by magnet independent) for beam offset less than 0.14 σ will be about 0.0025%, and tolerance of systematic fluctuation (same for all magnets) will be about 1%.
- Tolerance of random magnet strength fluctuation for emittance increase less than 0.063 ε_0 will be about 0.17%.
- The results suggests:

  Curved Linac (following earth curvature) will be fine,

  if magnet strength can be stable enough.