Low Emittance Transport in Long Straight Line of RTML, which is necessary for proposed change of ILC Layout

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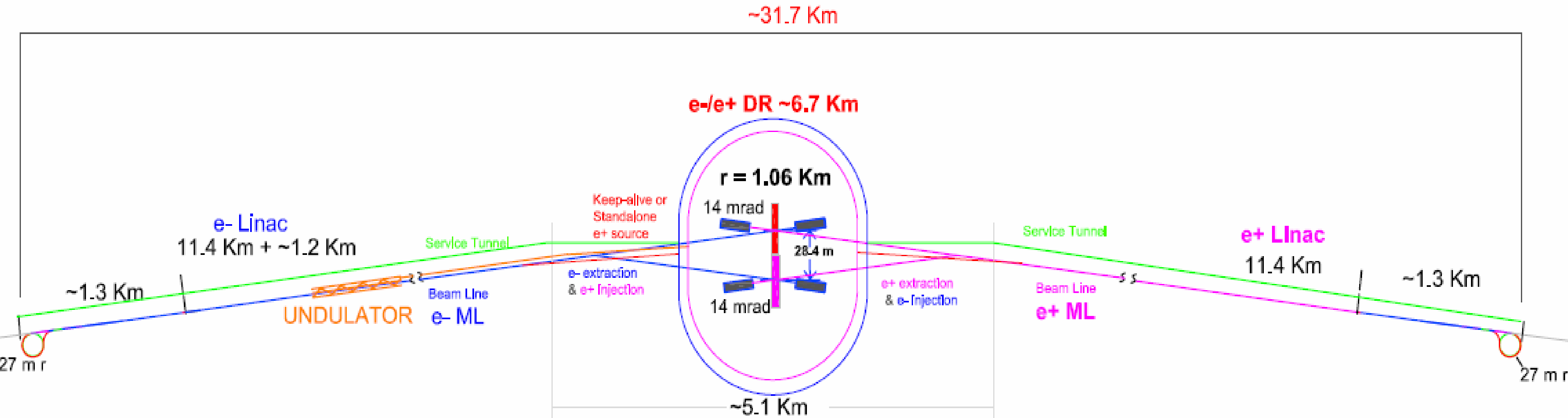
Long Transport in RTML

- DR may (will) be located at the center of ILC site.
- Need to transport low emittance, 5GeV beam. The length is approximately the length of the main linac.

(1) Orbit and emittance increase due to quad motion or misalignment

(2) Effect of Stray field.



From report by PATERSON, TENENBAUM, GARBINCIUS
Oct 23, 06

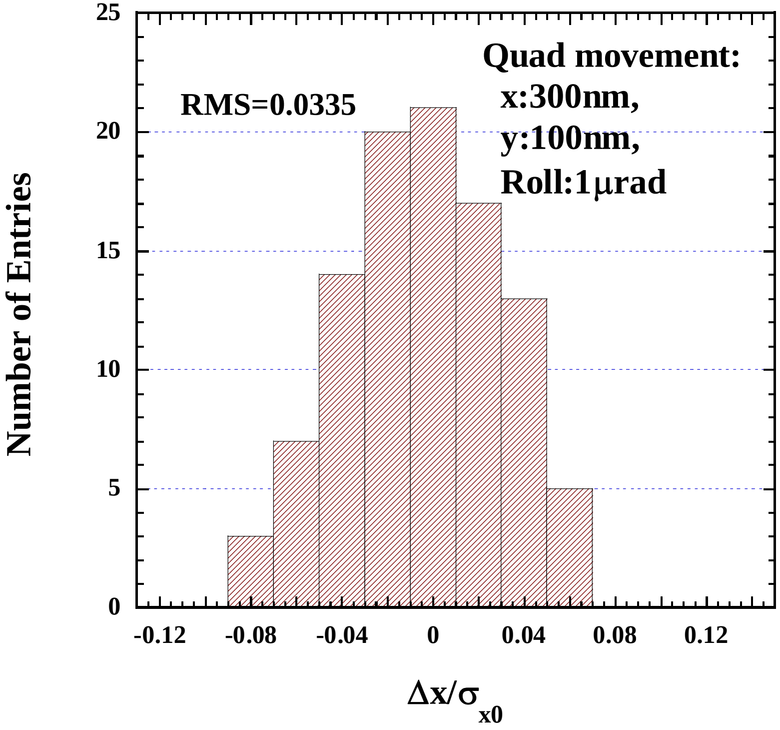
Schematic Layout of the 500 GeV Machine

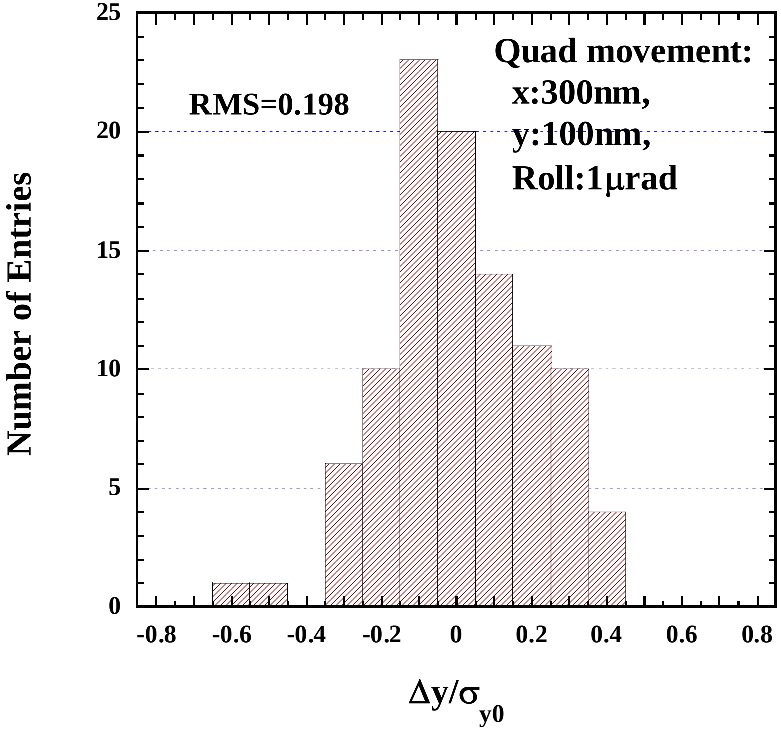
(1) Quad motion/misalignment. Simulated model

- Laser Straight Transport Line, 12 km.
- FODO Lattice, Quad Spacing 36 m, Phase advance x/y = 50/45 degree per FODO cell
- BPM and dipole correctors (x and y) are attached to every quad. Beam Energy 5 GeV, Initial normalized emittance x/y = 800/2 nm, energy spread 0.3% (it should have been set as 0.15%)
  - Perfect initial beam (orbit, matching etc.) is assumed.
- Tracking of 10000 macro-particles using computer code SAD
- Beam center position and/or vertical projected emittance at the end of the line are looked .

(1) Beam center position jitter due to quad motion, No corrections

RMS Quad offset x: 300 nm, y:100 nm, Roll: 1 μrad
100 random seeds.
Figures show distribution of beam offset at the end of the line





100 nm will be tolerable

(2) Kick minimization

Set Steering magnets to minimize:

$$\sum_i w^2 (x_i + \theta_{xi}/k_i)^2 + \sum_i x_i^2 \quad \text{and}$$

$$\sum_i w^2 (y_i - \theta_{yi}/k_i)^2 + \sum_i y_i^2$$

where x_i (y_i) is horizontal(vertical) reading of i-th BPM,

θ_{xi} (θ_{yi}) the kick angle of i-th steering magnet and

k_i the k-value of the i-th quad

(inverse of focsl length, positive for horizontal focus)

(Assuming the i-th BPM, i-th Quad and i-th Steering are attached.)

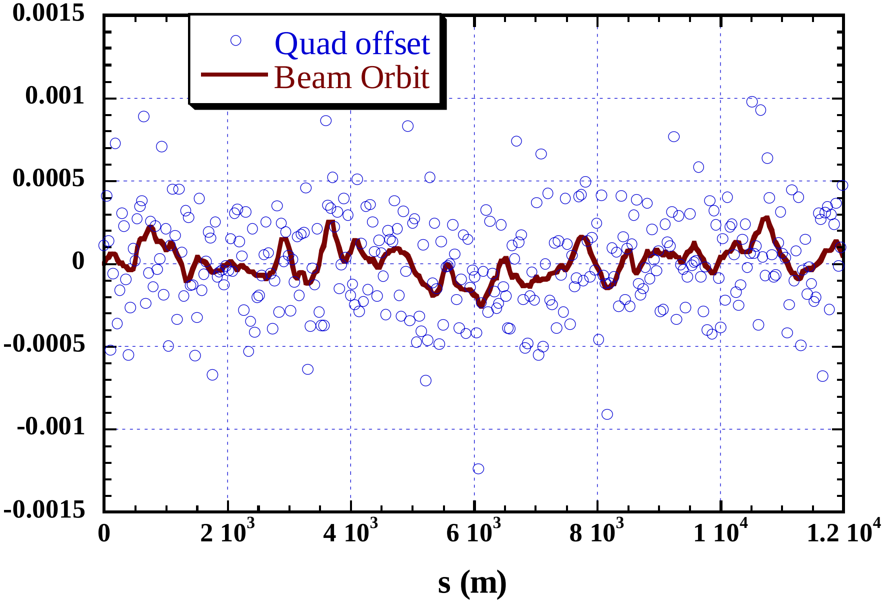
w is the weight factor (here, set as 10)

This correction intends to minimize total kick by quad and steering.
Expected to be better than 1-to-1, since BPM will be aligned w.r.t. quad more accurately than w.r.t. an ideal line.
But need some iterations and more time.

Example of Results of kick minimization

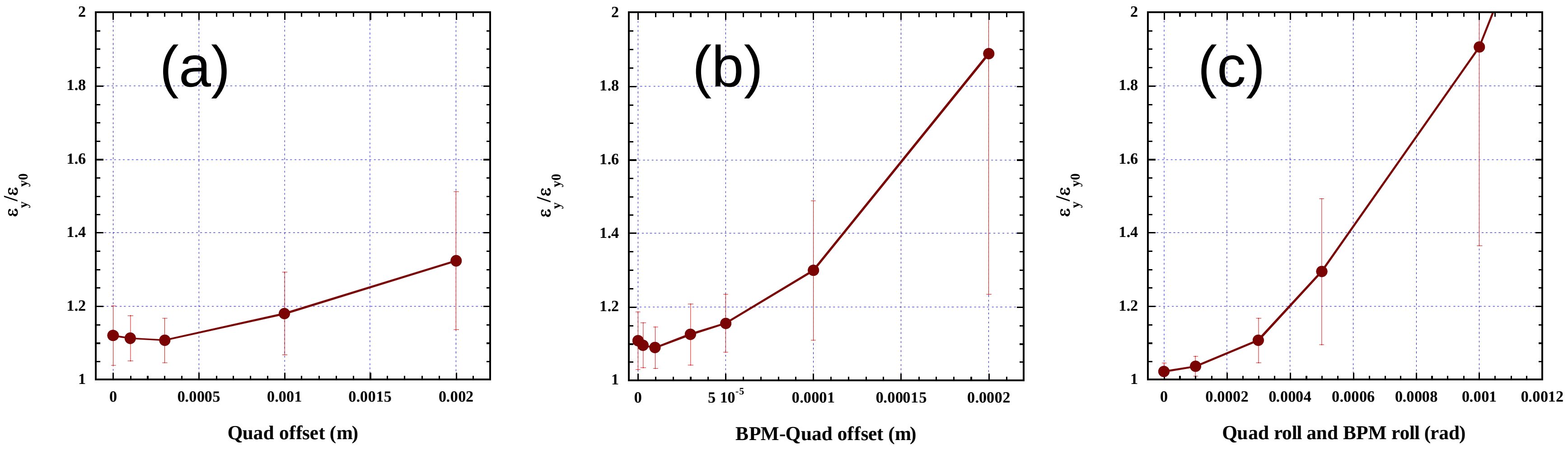
"Standard" errors:
Quad offset x and y: 300 μm, Quad roll: 300 μrad
BPM offset w.r.t. attached Quad: x and y: 30 μm,
BPM roll w.r.t. attached Quad: 300 μrad

Quad offset and Beam orbit (vertical)



Result of kick minimization

Sensitivity to different errors (average of 100 seeds)
(a) Quad offset (same in x and y)
(b) BPM offset w.r.t. attached Quad (same in x and y)
(c) Roll of Quad and Roll of BPM w.r.t. attached Quad
(Same value for both roll errors)
In each figure, other errors are kept as “standard”



“Standard” set errors (Quad offset 300 μm, roll 300 μrad, BPM-Quad offset 30 μm) will increase the emittance about 10%, mostly due to Quad roll error.

SUMMARY 1-1

No corrections (quad motion faster than feedback) :

- 100 nm RMS movements will cause beam position jitter about 0.2 sigma of the nominal beam size at the end of the beam line, which will be tolerable, considering the orbit feed-forward in the turnaround after this line.
  - Note that emittance increase in the line is small.
  - Emittance increase in the turnaround → see study (2)

Kick minimization:

- 300 μm RMS Quad offset and 30 μm RMS BPM-Quad relative offset error will be tolerable, using “Kick Minimization”.
  - Emittance increase less than 3% of nominal, without roll errors.
- 300 μrad Quad roll will increase emittance about 10%.
  - Kick Minimization does not correct x-y coupling
  - Corrections using skew quadrupoles (with good monitors) will mitigate the effect. (This correction is not studied here)

SUMMARY 1-2

Note:

By mistake, the initial energy spread was set as 0.3%, where our design is 0.15%. The emittance increase due to dispersive effect is overestimated by factor 4.

PRELIMINARY CONCLUSION

- Quad misalignment/motion in the long low emittance transport will not be a serious problem.

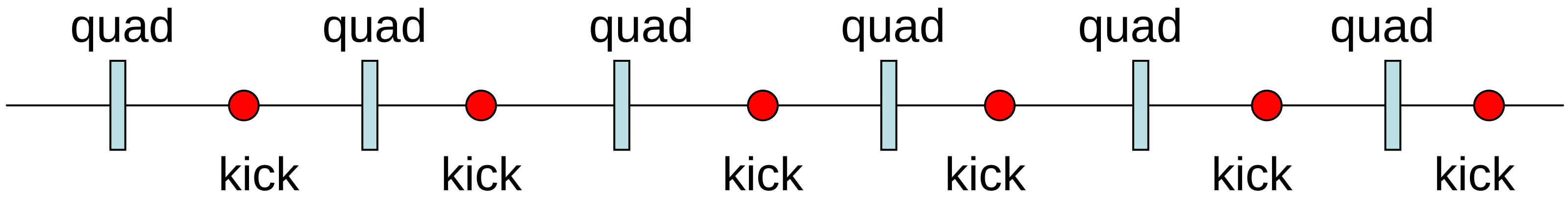
(2) Effect of Stray field.

Fast changing stray field affects beam orbit

- Orbit after turnaround will be corrected by feed-forward.
- Orbit in the turnaround will increase emittance.
- Emittance increase in the long transport line itself will be much less serious.

Assumptions and Approximations

- Straight beam line
- FODO lattice
- Kick by the stray fields between two consecutive quads are represented by a kick at one position, the center of the section.
- The stray field strength (integrated between two quads) is independent and random, and the RMS of the strength is constant along the beam line.
- There are many quads (Sections between them) and the effects can be treated statistically.



kick angle at i - th section : $\theta_i = l \dfrac{cB_i}{E}$

l : Length Between Quads, c : Speed of Light

B_i : Average of transverse (magnetic) field strength in the i - th section

$B_i = \int B(s) ds / l$

(B : magnetic field strength, integrate between quads, l : quad spacing)

E : Beam energy

Position change at the end of the beam line : $y = \sum_i \theta_i \sqrt{\beta \beta_i} \sin \varphi_i$

β : betafunction at the end, β_i : betafunction at i - th section,

φ_i : phase advance from i - th section to the end.

$\sqrt{\beta \beta_i} \sin \varphi_i$ is R_{12} from i - the section to the end of the line

RMS of position change at the end of the beam line:

$$\sqrt{\left\langle y^2 \right\rangle} = \sqrt{\left\langle \left[\sum_i \theta_i \sqrt{\beta \beta_i} \sin \varphi_i \right]^2 \right\rangle} \approx \sqrt{\beta \sum_i \left\langle \theta_i^2 \right\rangle \beta_i \sin^2 \varphi_i} \approx \frac{c}{E} \sqrt{\frac{L l \beta \overline{\beta}}{2}} B_{RMS}$$

$\left\langle \; \right\rangle$: average over ensemble, B_{RMS} : RMS of average of field

$L = l \times N_q$: Length of the beam line.

N_q : Number of quads

Here, we used

$$\left\langle \theta_i \theta_j \right\rangle = \begin{cases} 0 & (i \neq j) \\ \left\langle \theta_i^2 \right\rangle = \left(\dfrac{l c B_{RMS}}{E} \right)^2 & (i = j) \end{cases} ,$$

$\sin^2 \varphi_i \to 1/2$, $\beta_i \to \overline{\beta}$ (averages over many sections), then,

$$\sum_{\mathrm{i}} \left\langle \theta_i^2 \right\rangle \beta_i \sin^2 \varphi_i \to N_q \left(\frac{l c B_{RMS}}{E} \right)^2 \overline{\beta} \frac{1}{2}$$

If we Require the beam orbit jitter smaller than 10% of beam size,

$$\sqrt{\langle y^2 \rangle} < 0.1\,\sigma_y = 0.1\sqrt{\varepsilon\beta}, \quad B_{RMS} < 0.1\frac{E}{c}\sqrt{\frac{2\varepsilon}{Ll\bar{\beta}}} \quad (\varepsilon : \text{emittance}).$$

Using parameters; B_{RMS} : RMS of average field between two quads

$$\varepsilon = 2\times10^{-12}\ \text{m}, \quad E = 5\times10^{9}\ \text{eV}$$

$$L \approx 1\times10^{4}\ \text{m}, \quad l \approx 35\ \text{m}, \quad \bar{\beta} \approx 100\ \text{m (phase advance 45 deg./FODO cell)},$$

$$B_{RMS} < 1.0\times10^{-9}\ \text{T.} \quad \text{(without feed-forward.)}$$

This limit is inversely proportional to l (half length of FODO cell, note $\bar{\beta} \propto l$) and $\sqrt{L}$ (L is total length of the beam line).

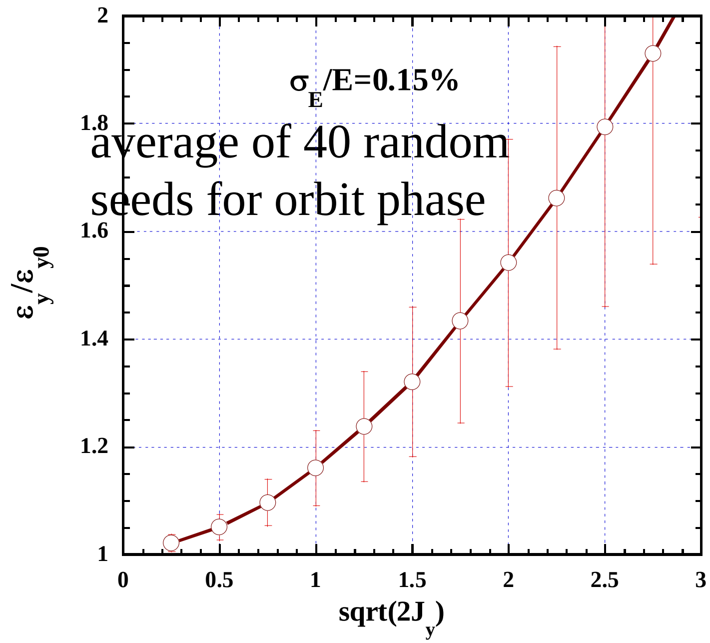
If we rely on the feed-forward in the turnaround after the long transport line, this limit is not relevant.

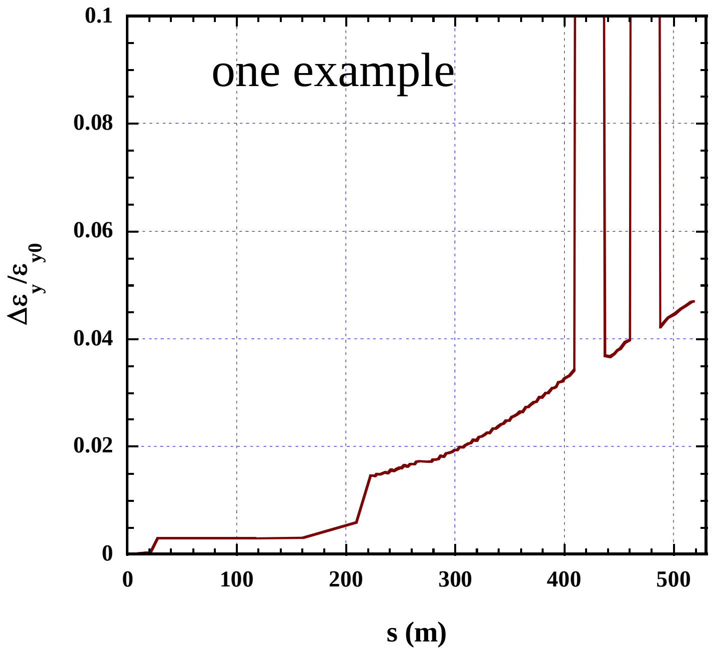
The limit will be from the emittance dilution due to dispersive effect in the turnaround caused by the orbit fluctuations.

Tracking simulation, emittance increase in the turnaround due to orbit jitter (baseline RTML before BC1), using SAD

Set orbit at the beginning of present version of RTML and looked at emittance at the entrance of Bunch Compressor, after the turnaround and spin rotator.

Initial $\gamma\varepsilon$ = 2E-8 m, σ_E/E =0.15%, 4000 macro-particles.





0.75-sigma jitter will be tolerable (5% emittance increase), then, requirement is

$$B_{RMS} < 7.5\times10^{-9}\ \mathrm{T.}\ \text{(with feed - forward)}$$

Summary 2

Tolerable orbit jitter in the turn-around is about 0.75-sigma, which increase emittance about 5% in the region of the turnaround, considering orbit feed-forward.
Then, requirement of stray field in the long (~10 km) straight section of the RTML will be

$$B_{RMS} < 7.5 \times 10^{-9}\ \mathrm{T}.$$

where B_{RMS} is the RMS of average stray field strength between two quads,

$$\int B_x(s)ds/l \qquad (B_x : \text{horizontal magnetic field, } l : \text{quad spacing})$$

We assumed this average is independent and random for each section.

This limit is relevant for fields which change faster than orbit feedback, either inter-pulse or intra-pulse.

Note:
Detailed study of effects of stray fields in NLC: see reference [3].

Comment to the reference [2] from P.Tenembaum:
“If I look at the ESB (End Station B at SLAC) measurements [3], which showed a 2 nT field when 60 Hz harmonics were suppressed, that would suggest about a 0.2 sigy RMS jitter. That's probably tolerable, if not particularly optimal. “

References:

[1] K.Kubo, ILC-Asia Note 2006-06A
http://lcdev.kek.jp/ILCAsiaNotes/2006/ILCAsia2006-06A.pdf

[2] K.Kubo, ILC-Asia Note 2006-05
http://lcdev.kek.jp/ILCAsiaNotes/2006/ILCAsia2006-05.pdf

[3] J. Frisch, T.O. Raubenheimer, P. Tenenbaum
http://www-project.slac.stanford.edu/lc/ilc/TechNotes/LCCNotes/PDF/LCC-0140.pdf