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LUMINOSITY IMPROVEMENT AT 250GEV CM

The luminosity at the center-of-mass energy 250GeV can be improved by factor ~1.65 by adopting the horizontal emittance at IP factor 2 smaller than in the TDR. This is achieved by modifying the damping ring design slightly.

RATIONALE

The luminosity at 250GeV CM is 0.82×10^{34} /cm^2/s in the present ILC parameter set (0.75×10^{34} in the TDR but this has been corrected in the Change Request 5). The TDR gave the machine design optimized for the center-of-mass energy 500GeV and listed the parameters (TDR vol. 3.II, Table 2.1) for lower energies by simply changing the optics in the Beam Delivery System. A slightly different parameter set would be better, if we put more emphasis at lower energy operation, in particular if the machine is to be built for 250GeV CM in the first stage.

There are several possible ways to improve the luminosity. In this change request we adopt the following way.

1. Change the lattice of the damping rings to reduce the normalized horizontal emittance from ~6μm (slightly depending on the operation mode) to ~4 μm
2. Revisit the emittance increase from the damping rings to IP. It turned out the emittance at IP can be reduced from 10 μm to 5 μm.
3. With the same optics in BDS as in the TDR the horizontal beam size can be reduced by a factor $\sqrt{2}$.
4. This will increase the geometric luminosity by the same factor. Owing to the enhanced pinch effect due to the smaller beam size, the actual luminosity will be increased by ~1.65.

There are several side effects.

1. The energy loss by the beamstrahlung will increase about a factor ~2.6. Also, the background from the incoherent pair creation increases by factor ~3.

2. The vertical disruption parameter increases from ~25 to ~35. This might require more accurate IP position control but within the manageable range.

Since the present design change causes an increase of beamstrahlung, it cannot improve the luminosity at 500GeV, where the beamstrahlung is already high. However, the smaller horizontal emittance at least has a merit of easier tuning procedure of BDS at any energies.

The Table.1 shows the new parameter set at 250GeV together with the old ones at 250GeV and 500GeV.

Table.1. TDR parameters at 250/500GeV and the new parameters

		TDR		New
Ecm	GeV	250	500	250
N	e10	2.0	2.0	2.0
Collision frequency	Hz	5.0	5.0	5.0
Electron linac rep rate	Hz	10.0	5.0	5.0
Nb		1312	1312	1312
Bunch separation	ns	554	554	554
Beam current	mA	5.78	5.78	5.78
P_B	MW	5.3	10.5	5.3
σ_z	mm	0.3	0.3	0.3
σ_E/E(e-)	%	0.188	0.124	0.188
σ_E/E(e+)	%	0.15	0.07	0.15
ε_{nx}	μm	10.00	10.00	5.00
ε_{ny}	nm	35.0	35.0	35.0
electron polarization	%	80	80	80
positron polarization	%	30	30	30
β_x	mm	13.0	11.0	13.0
β_y	mm	0.41	0.48	0.41
σ_x	nm	729.0	474.2	515.5
σ_y	nm	7.66	5.86	7.66
θ_x	μr	56.1	43.1	39.7
θ_y	μr	18.7	12.2	18.7
Dx		0.26	0.30	0.51
Dy		24.5	24.6	34.5
Upsilon (average)		0.020	0.062	0.028
Ngamma		1.21	1.82	1.91
δ_{BS}	%	0.97	4.50	2.62
Lgeo	1.0E+34	0.374	0.751	0.529
L (simulation, waist shift)	1.0E+34	0.82	1.79	1.35

SCOPE: Damping Rings and BDS/MDI

The damping ring design must be changed. Actually, longer dipole magnets in the arcs are to be adopted as will be described later. The basic optics in the BDS does not change (same beta functions at IP) but it should be studied in detail

VALUE/SCHEDULE IMPACT: ALMOST NONE

The dipole magnets in DR are longer than in the TDR but the BL (magnetic field times length) is the same. Cost change will be quite small. Construction schedule will not change. The commissioning time of DR may increase (due to the smaller emittance) and that of the BDS may decrease (owing to the larger collimation depth). These are quite hard to estimate but should anyway be negligible.

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DETAILED DESCRIPTION OF THE CHANGE REQUEST

1. Possible Ways of Luminosity Improvement

The luminosity can be expressed by the formula

$$\mathcal{L} \approx C\frac{P_B}{E}\sqrt{\frac{\delta_{BS}}{\epsilon_{y,n}}}\min\left(1, \sqrt{\sigma_z/\beta_y}\right)$$

where

- C: universal constant including natural constants only
- E: beam energy
- P_B: beam power
- δ_{BS}: the average energy loss by the beamstrahlung which can be written as

$$\delta_{BS} = \left\langle -\frac{\Delta E}{E}\right\rangle \approx 0.836\frac{N^2 r_e^3\gamma}{\sigma_z\sigma_x^2}, \qquad (\Upsilon \ll 1,\ \sigma_x \gg \sigma_y)$$

- $\varepsilon_{y,n}$: normalized vertical emittance at IP
- $\sigma_{x,y,z}$: r.m.s. bunch size in x and y plan, and the bunch length
- β_y: vertical beta function
- The last factor min( ) comes from the hour-glass effect.

There are three parameters which can be changed: P_B, $\varepsilon_{y,n}$, δ_{BS}.

P_B can be increased by increasing the number bunches (e.g. 2625 bunches) or by increasing the repetition rate (e.g., 10Hz operation). However, these are quite costly (larger RF system of the man linacs and/or damping ring reinforcement).

To reduce $\varepsilon_{y,n}$ might be possible in the damping rings by more accurate beam tuning. However, this also demands tighter alignment tolerance of the main linacs, which is not reasonable since the cryomodule design has been fixed already. (Nonetheless, to reduce $\varepsilon_{y,n}$ may be achieved after long experience of operation in the future.)

Hence, to accept larger δ_{BS} is the only way that does not require significant cost increase and alignment improvement. The TDR parameter set gives δ_{BS} ~1% at 250GeV, in comparison to ~4% at 500GeV. There is still a room to accept larger δ_{BS} at 250GeV.

The energy loss by beamstrahlung can be written as

$$\delta_{BS} = \left\langle -\frac{\Delta E}{E}\right\rangle \approx 0.836\frac{N^2 r_e^3\gamma}{\sigma_z\sigma_x^2}, \qquad (\Upsilon \ll 1,\ \sigma_x \gg \sigma_y)$$

where

- N: Number of electrons/positrons per bunch
- r_e : classical electron radius
- $\gamma = E/mc^2$

One must note that N/σ_z cannot be increased without the design change of the detector and the interaction region because the out-coming angle of the incoherent electron/positron pairs is approximately proportional to $(N/\sigma_z)^{1/2}$.

Under this condition δ_{BS} can be increased by increasing $N \rightarrow aN$ and $\sigma_z \rightarrow a\sigma_z$ (a>1). The former implicitly means to decrease the number of bunches in a pulse as 1/a since P_B must be fixed. The latter means $\beta_y \rightarrow a\beta_y$ and $\sigma_y \rightarrow \sqrt{a}\ \sigma_y$ (due to the hour-glass factor). Then, $\delta_{BS} \rightarrow a\,\delta_{BS}$ and $L \rightarrow \sqrt{a}\ L$. However, this choice changes the single-bunch effects in DR and makes tighter the vertical alignment tolerance in the main linacs (proportional to 1/N).

Thus the possible choice for larger δ_{BS} is to decrease the horizontal beam size $\sigma_x \rightarrow \sigma_x/a$, then $\delta_{BS} \rightarrow a^2\,\delta_{BS}$ and $L \rightarrow aL$.

Now, how to reduce σ_x? The simplest way is to reduce β_x. However, this will make the beam divergence angle at IP larger;

$$\theta_x^* = \sqrt{\frac{\epsilon_{x,n}}{\gamma\beta_x^*}}$$

which causes larger horizontal beam size in the final quadrupole magnet QD0. Then, the synchrotron radiation from beam halo will hit the magnet and cause background to the experiments. Usually, this problem is cured by scraping out the halo particles in the collimator upstream, but in our design for 250GeV the collimation depth is already as small as $\sim 6\sigma_x$. We cannot collimate deeper. Hence, we can reduce the horizontal beam size only by reducing the horizontal emittance $\varepsilon_{x,n} \rightarrow \varepsilon_{x,n}/a$.

With this choice, if we do not change β_x, then $\sigma_x \rightarrow \sigma_x/\sqrt{a}$, $\delta_{BS} \rightarrow a\delta_{BS}$ and $L \rightarrow \sqrt{a}L$. From the view point of the beam divergence angle, we can further reduce σ_x by $\beta_x \rightarrow \beta_x/\sqrt{a}$. Then, $\delta_{BS} \rightarrow a^2\,\delta_{BS}$ and $L \rightarrow aL$. We do not include the latter possibility for the baseline parameter set in the present change request but it can still be a choice in the actual operation (it does not require further change of hardware).

2. The Damping Rings with Smaller Horizontal Emittance

The present DR design gives the normalized horizontal emittance ε_{xn} ~6.3μm (re-computed by SAD including the intrabeam scattering). More than 10 years have passed since the DR was designed. Since then many rings as the light sources and also as ring colliders have been designed with elaborated optics giving lower emittances. TDR DR design by now is considered to be conservative. Here, we shall adopt a simple change of optics from TDR DR, though more aggressive optics may be feasible.

The layout of the arc cell in TDR DR contains 1.5m drift space between the dipole and quadrupole magnets. This space is reserved for the pillars to support the electron ring components lifted above the positron ring. It may be reduced to 0.5m by changing the design of the support so that the effective length of the dipoles is lengthened 3m → 5m (see Fig.1). (5m dipole will be split for actual construction).

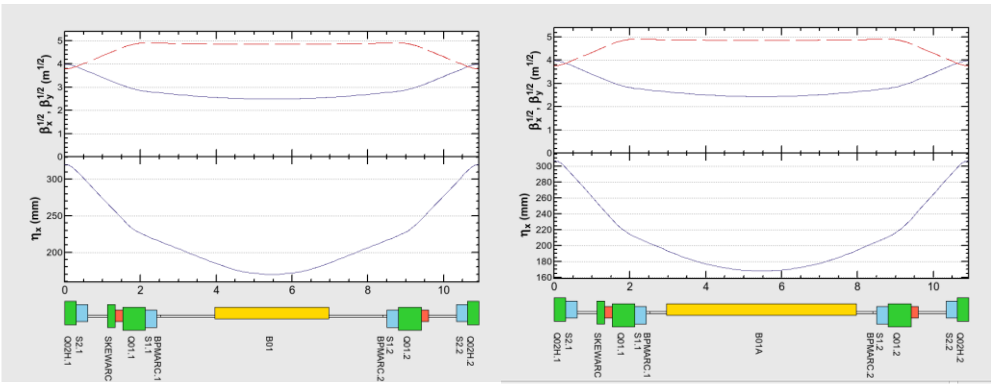


Fig.1. TDR (left) and new (right) layout of the arc cell and the optics.

The emittances and the damping times were computed by using SAD including the effects of intrabeam scattering (IBS) (see K. Kubo [1] for details). The new optics gives $\varepsilon_{x,n}$ ~4μm.

Table.2. DR parameters, TDR and the new.

	TDR	New optics
$\varepsilon_{x,n}$ (μm)	5.74	3.14
$\varepsilon_{x,n}$ with IBS (μm)	6.27	3.97
Tune (x/y)	48.26/26.76	49.33/26.86
Phase advance/2π x/y	0.21891 / 0.08098	0.2250 / 0.0808
Damping time x/y/z (ms)	23.9 / 23.9 / 11.9	25.5 / 25.5 / 12.8

There are other possible choices of change, other than the longer bend even within the scheme of the so-called TME. However, the choice of stronger quadrupoles with the TDR magnet layout or the choice of increased number of arc cells do not give sufficiently wide dynamics aperture, though they give the required horizontal emittance. On the other hand, the present choice of longer dipoles gives sufficient aperture as shown in Fig.2. Degradation of aperture due to magnet errors has been checked and turned out not to be significant.

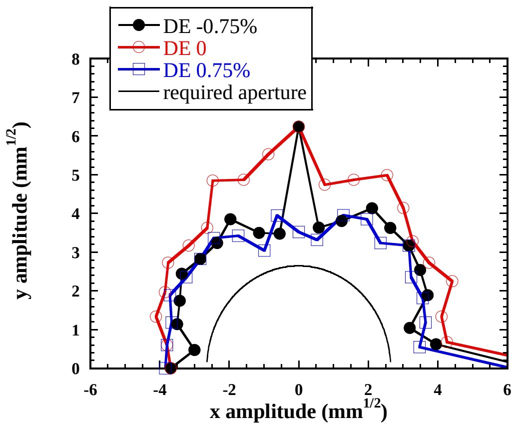


Fig.2. Dynamic aperture in the new design without errors

One of the keys in the design of the positron DR is the electron cloud instability. The electron cloud density generated by the positron beam does not depend on the beam emittance. On the other hand the threshold density will be reduced as $(\sigma_x)^{1/2}$, which in our case means $(\varepsilon_{x,n})^{1/4}$, i.e., ~20% reduction, since the beta function is more or less the same as in TDR. The TDR says the expected density is factor ~3 below the threshold. Therefore, the reduction of $\varepsilon_{x,n}$ by factor 2 will still be safe.

3. Transport from the DR to the IP

TDR quotes the following values of $\varepsilon_{x,n}$

- At IP : 10μm
- At main linac exit : 9.4μm
- At main linac entrance : 8.4μm
- Growth in RTML : 0.9μm
- DR exit : 6.3μm

It seems the emittance increases other than 0.9μm in RTML (due to synchrotron radiation) are overestimation. The vertical emittance increase in the main linac is less than 15nm. The increase in the horizontal plane should not be much larger than this. There is also an unidentified increase 8.4 - 0.9 - 6.3 = 1.2 μm. There is a dogleg right after the undulator section in the electron linac to separate the electron beam from the produced positrons. Horizontal emittance increase due to the synchrotron radiation in this dogleg is totally negligible at 250GeV CM (proportional to E^6). Hence, if $\varepsilon_{x,n}$ at DR exit is 4μm, $\varepsilon_{x,n}$ =5 μm is considered to be achievable at the IP.

4. Beam-Beam Interaction

The simple scaling to the horizontal emittance as described in Sec.1 says δ_{BS} should increase by factor 2 and the luminosity by factor $\sqrt{2}$. Since the horizontal disruption parameter D_x is now ~0.5 (proportional to $1/\sigma_x^2$. see Table 1), the pinch effects in the horizontal plane is no longer negligible. Due to this effect the increase of δ_{BS} and luminosity is more than the simple scaling (the simulation result is 2.7 and 1.65, respectively). The number of beamstrahlung photons also increases by factor 1.58 rather than $\sqrt{2}$.

Detailed simulation has been performed by D. Jeans [2]. The simulations included 3 cases together with TDR. The case (A) is the parameter set for the present change request (change of $\varepsilon_{x,n}$ only). The case (B) aims at further luminosity increase with a smaller β_x. (C) is intended to cure the too large disruption parameter in (B) by adopting a larger β_y.

Table.2 Beam-beam simulation parameters, compared with the TDR value

	$\varepsilon_{x,n}$	β_x	β_y
TDR	1	1	1
(A)	1/2	1	1
(B)	1/2	$1/\sqrt{2}$	1
(C)	1/2	$1/\sqrt{2}$	$\sqrt{2}$

One of the issues of increased beamstrahlung is the center-of-mass energy spread. Table 3 shows the luminosities near the maximum center-of-mass energy.

Table 3. Luminosities near the maximum center-of-mass energy 250GeV. The numbers in ( ) are the enhancement with respect to the TDR vales. (Note the value 0.808 for L_{total} for TDR is slightly different from the (corrected) TDR value 0.82. This is within the simulation accuracy.)

10^{34} /cm^2/s	L (total)	L ($\sqrt{s}$ >90%)	L ($\sqrt{s}$ >95%)	L ($\sqrt{s}$ >99%)
TDR	0.808	0.808	0.799	0.697
(A)	1.37 (x 1.69)	1.35 (x 1.68)	1.29 (x 1.62)	0.990 (x 1.41)
(B)	1.97 (x 2.44)	1.90 (x 2.35)	1.72 (x 2.15)	1.18 (x 1.69)
(C)	1.80 (x 2.23)	1.73 (x 2.15)	1.57 (x 1.97)	1.08 (x 1.55)

Another influence of the increased beamstrahlung is the increased number of incoherent pairs of electron and positron. The production of the incoherent pairs is dominated by the three processes:

Landau-Lifshitz process $e^+ e^- \rightarrow e^+ e^- e^+ e^-$
Bethe-Heitler process $e^{+(-)} \gamma \rightarrow e^{+(-)} e^+ e^-$
Breit-Wheeler process $\gamma \gamma \rightarrow e^+ e^-$

where γ is the beamstrahlung photons. The number of photons from these processes is proportional to L, Ln_γ, Ln_γ^2, respectively, where n_γ is the number of beamstrahlung photons from one electron (positron). These processes contribute about 27%, 68%, and 5% of the pairs, respectively, for the case (A). The expected increase of the pairs is more than that of the luminosity since n_γ also increases by smaller σ_x. The out-coming angle of the pairs does not change from the simple scaling $(N/\sigma_z)^{1/2}$ but it seems to increase slightly due to the non-leading terms.

The vertical disruption parameter D_y, which is proportional to $1/\sigma_x$, increases from the TDR value ~25 to ~35 for (A) and (C), and to ~42 for (B). The luminosity would be more sensitive to the vertical beam positioning error Δy. Fig.3 shows a simulation result.

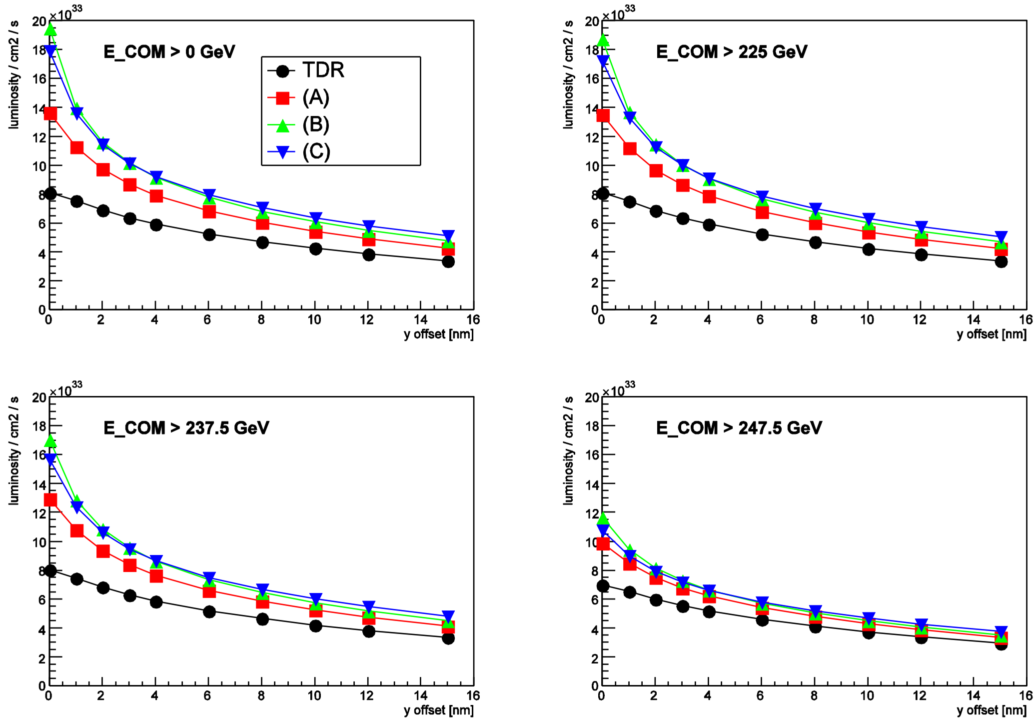
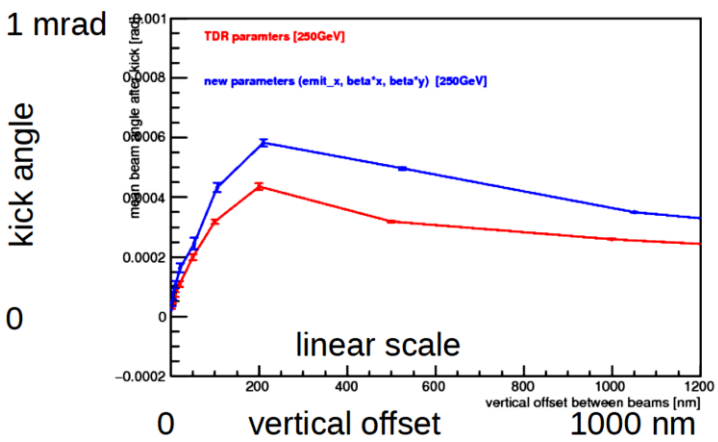


Fig.3. Luminosity (L_{total}, $L_{90\%}$, $L_{95\%}$, $L_{99\%}$) vs. beam vertical position error Δy for the 4 cases, TDR, (A), (B), and (C) (black, red, green, blue, respectively).

The luminosity is more sensitive to Δy than TDR case as expected, but the tolerance of Δy in units of nm (not in σ_y) is not tighter than at 500GeV (where σ_y is smaller). The simulation includes only parallel offset of the beam. More complex case such as slope (Δy linearly proportional to z), banana shape (quadratic), etc. should later be examined.



(from D.Jones)

Fig. 4. Beam-beam kick angle as a function of the vertical beam offset Δy for TDR (red) and (C) (blue).

Fig.4 shows the beam-beam kick angle as a function of the vertical beam offset Δy for TDR and (C). The kick angle is obviously larger but the dynamic range of the feedback (~Δy at the peak of the kick) does not decrease.

5. Additional Comments

The reduced $\varepsilon_{x,n}$ does not bring about luminosity increase at higher energies because the beamstrahlung is already large at these energies (may help a bit at 350GeV, where δ_{BS} ~ 1.9% in TDR).

However, smaller $\varepsilon_{x,n}$ allows larger β_x to achieve the same σ_x and makes the collimation depth larger. Therefore, the tuning of BDS will become easier, though it is hard to visualize.

6. What Must Be Studied in the Future?

There are several items which require further studies

- DR
  So far the electron cloud instability is estimated by a simple scaling law. Detailed simulation is needed. The support mechanics of the second level components must be revisited.
- Transport
  Horizontal dynamics from DR exit to IP must be revisited
- Beam-beam interaction
  Effects of beam shape (slope/banana) must be studied.
- Detector
  The beam-beam interaction would be significantly severer than with the TDR parameters. Increased beamstrahlung and incoherent pairs can have serious effects on the measurements. Background estimation should be done in more detail.
- Physics
  The time needed for reaching a specific integrated luminosity obviously becomes shorter, but simulation studies must be done under larger beamstrahlung and incoherent pairs.

REFERENCES

1 K. Kubo, AWLC2017 https://agenda.linearcollider.org/event/7507/contributions/39347/attachments/31809/47970/LowHemitILCDR-ALCWS.pdf

2 D. Jeans, AWLC2017 https://agenda.linearcollider.org/event/7507/contributions/39291/attachments/31828/48012/mdi-beamparams-awlc-2017.pdf

ATTACHMENTS:

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Change History:

Version:	modified:	by:	what:

IMPLEMENTATION PLAN

Can be left blank for first submission.

Concerned Parties (Work Packages, Coordinators, Suppliers etc.)

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Affected documents

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