Estimation of Collimation Depths for 20 and 2 mrad ILC BDS Lattices

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Abstract

Collimation depths are calculated for the current ILC BDS lattices for 20 and 2 mrad crossing angles, based on synchrotron radiation clearance through the apertures close to interaction region. A linear optics code\(^2\) is used which computes the transport of beam phase space and corresponding synchrotron radiation envelope through the final doublet and interaction region apertures. The collimation depth for the 20 mrad final doublet is found to be 9.6 \(\sigma_x\) (horizontal) 73.9 \(\sigma_y\) (vertical). The collimation depth for the 2 mrad final doublet is found to be 10.5 \(\sigma_x\) (horizontal) 66.8 \(\sigma_y\) (vertical).

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1 Introduction
The collimation depths of the ILC BDS lattice designs are determined predominantly by the synchrotron radiation fan generated in the final doublets. The generated photons may be high energy and thus need to pass cleanly through the interaction region, rather than being intercepted near the IP by masks, which may actually generate background.
Collimation depths have been calculated for previous BDS designs, TESLA and NLC. For TESLA a linear optics code (DBLT, O. Napoly, CEA Saclay) was used. This code, with a few modifications to account for the differences in the ILC design, is used here. The ILC BDS baseline design has two finite-crossing angle schemes (20 mrad and 2 mrad) each imposing different constraints on the synchrotron radiation clearance, resulting in different collimation depths.
It should be noted that in practice, collimation depths will be determined by the behaviour of the halo phase space envelope in the final doublet, and the transport of the halo phase space from the betatron collimation spoilers and the final doublet. The DBLT code is only concerned with the first of these problems, and assumes perfect linear transport between the betatron spoilers and the final doublet.
The simplifications of the method should also be outlined immediately. The collimation depth estimations here are based on linear particle transport through the final doublet. Thus the effect of the local chromaticity correction (specifically the interleaved sextupole) is not taken into account, nor is the effect of the tail-folding octupole. In addition, off-energy particles are not considered. These simplifications will certainly affect the collimation depth, and more detailed simulations should be used to quantify them.
The choice of beam parameters is an essential part of the collimation depth calculations. For comparison purposes, the same beam parameters should be used when calculating the collimation depths for different crossing angles. However the beam parameters used in the lattice designs for 2 mrad and 20 mrad must be respected, which for historical reasons are different. The parameters used in each case are clearly stated in the results section.

2 Method
The synchrotron radiation fan algorithm DBLT is described elsewhere in detail. The key features of the theory will be outlined again here. The collimation system described in applies directly to the ILC collimation system with 2 spoilers. The spoiler have betatron-phase differences of 0 and π/2 with the IP. The collimated beam phase space corners at distance s upstream from the IP in the final doublet are given by

\[
\begin{pmatrix}
x_C \\
x'_C
\end{pmatrix}
= R^{-1}(s)
\begin{pmatrix}
N_x \sqrt{\beta^*_x \epsilon_x} \\
N_x \sqrt{\gamma^*_x \epsilon_x}
\end{pmatrix}
\tag{1}
\]

(and identically for y) where \( R \) is the transfer matrix from the position s to the IP, \( N_x \) is the collimation depth in units of beam size, \( \beta^*_x \) and \( \gamma^*_x \) are the Twiss parameters at the IP, \( \epsilon_x \) is the emittance. This assumes a perfect linear transportation of the phase space between the betatron spoilers and the final doublet.
Thus the maximum \( x \) of the SR photons (which defines the SR fan envelope) after travelling longitudinal distance L from the emission point in the final doublet is given by

\[
x'_C = x_C + L x'_C,
\]
and identically for y. Thus the maximum transverse radial displacement of the SR photon for a given emission point is

\[
r = \sqrt{(x'_C)^2 + (y'_C)^2}
\tag{2}
\]
and the constraint imposed by requiring the SR fan to pass through an aperture of radius $a$ is $r \leq a$. This constraint which determines the solutions for $N_x$, $N_y$, for one particular emission point. It should be noted that constraint (2) does not demand a unique solution for $N_x$, $N_y$ but rather an elliptical curve in $N_x$, $N_y$ space. However the solution usually chosen is that which maximises $N_x \times N_y$.

Obviously there are many emission points in the final doublet and thus many corresponding solution ellipses. In practice the beam phase space envelope (1) is computed for many points through the final doublet; these points serve as emission points for SR and the solution ellipses for a given constraining aperture are computed for each emission point. The overall solution is the smallest pair of $N_x$, $N_y$ values. This process must be repeated for each small aperture in the interaction region. An example of how these solutions appear in $N_x$, $N_y$ space can be seen in Figure 2 of reference.

The apertures in question may include the following: the narrow beampipe at the interaction point, forward instrumentation devices and masks, and the apertures of the extraction quadrupoles. These apertures may not impose circularly symmetric constraints (such as $r \leq a$ above) on the collimation depth. The details of the aperture constraints are discussed in the next section.

The evaluation of the collimation depths may become complicated by the fact that the corresponding solution ellipses may intersect. This may arise from the constraints imposed by one aperture on two or more SR emission points, or the constraints imposed by two or more different apertures on two or more SR emission points. If this is the case the maximum value of $N_x \times N_y$ on each solution ellipse may fall into the forbidden region and thus neither solution is allowed. A simple illustration is given of this in Figure 1, where the solution boundary is non-elliptical. In such cases, the collimation depth is given by the overall maximum value of $N_x \times N_y$ on the non-elliptical solution boundary, which is the point where the two ellipses cross.

![Figure 1. Collimation depth solution where two constraints define the solution boundary. Each ellipse corresponds to a boundary constraint on $N_x$, $N_y$ imposed by a SR ray from a given emission point passing through an given aperture. The overall boundary of allowed $N_x$, $N_y$ values is indicated by the ‘allowed region’. All other ellipse boundaries for other SR emission points which are not crucial are not drawn.](image-url)
One further point worth mentioning is that the inverse of matrix $R$ need not be computed in order to compute $\begin{pmatrix} x_C \\ x_C' \end{pmatrix}$. It is sufficient to reverse the angle at the IP and transport using the non-inverted matrix

$$\begin{pmatrix} x_C \\ -x_C' \end{pmatrix} = R(s) \begin{pmatrix} N_s \sqrt{\beta^*_s \epsilon_s} \\ -N_s \sqrt{\beta^*_s \epsilon_s} \end{pmatrix}$$

since avoiding matrix inversion is computationally favourable.

### 3 Input Parameters: Interaction Region Geometry and Apertures.

The machine-detector interface for the two interaction regions are different, for historical reasons. For example, the 20 mrad lattice has been designed for $L^*=3.51$ m, while the 2 mrad lattice has been designed for $L^*=4.5$ m.

There is also the complexity of three different detector designs SID (Silicon Detector), LDC (Large Detector Concept), GLD (Gaseous Large Detector). In principle, all three detector designs contain small apertures due to forward instrumentation (the luminosity calorimeter and beam calorimeter) and detector masking. An example of the machine-detector interface for the LDC can be seen in Figure 2.

![Figure 2](image-url)

Figure 2. Machine detector interface of the Large Detector Concept, showing the narrow apertures in the interaction region.

Differences in the forward apertures can arise between different designs. It is also likely that the sizes of these apertures are not fixed and may be optimised as the design evolves.

Confusion may also arise about the orientation of these apertures with respect to the various important axes; those of the incoming and outgoing beam, and that of the detector, which are...
clearly not parallel for finite beam crossing angle. The orientation of apertures in this respect will be explicitly described in the calculations shown here.

All the above parameters will affect the calculated collimation depth. While some uncertainty exists about the values of those parameters, the best that can be done here is to clearly state the assumptions made and where possible take a conservative approach when estimating collimation depths.

4 Collimation Depth Calculations

4.1 20 mrad Final Doublet

The 20 mrad lattice offers the simplest analysis since the extracted beam passes through its own dedicated extraction line and does not interfere with the magnets of the other incoming beamline. The 20 mrad lattice has been designed with $L^* = 3.51$ which is most appropriate to the SID detector. An aperture of radius 12mm is placed close to the first extraction quadrupole (which could represent a beamcal/mask and is same radius as the beam pipe at the vertex detector). This aperture is centred on the axis of the extraction quadrupoles.

The analysis of the 20 mrad case reveals that the constraining aperture is the exit of the first extraction quadrupole (aperture of 13 mm), resulting in a collimation depth of $N_x = 9.56$, $N_y = 73.91$. The SR fan envelope for this collimation depth is shown in Figure 3. The apertures of the IP beam pipe and the mask (the mask just visible before the first extraction quadrupole) are clearly looser constraints than the first extraction quadrupole.

![Figure 3. Synchrotron radiation envelope for 20 mrad lattice for a collimation depth of $N_x = 9.56$, $N_y = 73.91$. The black rectangles illustrate (from left to right) the apertures of the final doublet and the extraction quadrupoles. It can be seen that the exit of the first extraction quadrupole imposes the constraint on the SR fan.](image)

The final doublet parameters used were taken directly from the ILC-FF9 deck (available on the web). The IP beam parameters were taken from TESLA 250GeV design $\beta^*_x,y=15\text{mm},0.4\text{mm}$, $\gamma_{x,y}=1\times10^{-7}\text{m}$, $3\times10^{-8}\text{m}$. Since the ILC-FF9 final doublet available in
the MAD deck has not been designed for the ILC-nominal parameters ($\beta^*_{x,y} = 21\text{mm}, 0.4\text{mm}$) but for the TESLA parameters ($\beta^*_{x,y} = 15\text{mm}, 0.4\text{mm}$), the IP beam parameters were taken from the TESLA 250 GeV design and they are fully compatible with the selected doublet.

4.2 2 mrad Final Doublet

The 2 mrad case is more difficult to analyse since the extracted beam passes through the final quadrupole of the other incoming beamline. The SR fan therefore passes through apertures off-centre and circular symmetry is broken. The IR geometry may also be quite different to that of the 20 mrad, since the 2 mrad lattice has been designed with the LDC in mind, with $L^* = 4.5 \text{ m}$.

In the 2 mrad case the synchrotron the radiation fan passes through the aperture of the final quadrupole of the opposite incoming beamline. See Figure 4

![Diagram of various axes and apertures in the 2 mrad interaction region](image)

**Figure 4.** Representation of various axes and apertures in the 2 mrad interaction region. The dotted line represents the QD axis (incoming beam), the dashed line represents the axis of the other QD (and the outgoing beam). The solid line represents the detector axis. The black rectangles represents the beamcal/detector mask, fixed on the detector axis.

The non-symmetrical apertures in the interaction region would lead to non-symmetrical constraints on the collimation depths. However for simplicity here, symmetrical constraints are defined in the following way. Consider the mask exit aperture in Figure 4 as it would appear looking along the line of sight of the outgoing beam or SR fan centroid. This is demonstrated in Figure 5
An imaginary symmetrical aperture can be constructed inside the real aperture. If this imaginary aperture is used as a constraint in the collimation depth calculation, it will ensure that the SR fan passes cleanly through the real aperture. In Figure 5 this imaginary aperture is shown as the dashed circle.

The apertures near interaction point that the SR must pass through include the beamcal/mask, the QD aperture, and the 'pocket aperture' in the QFiv. The assumption is made that the QF is far enough from the IP that SR hitting this aperture will produce negligible background at the detector. Preliminary studies have indicated that a beamcal radius of 20 mm results in much more backscattered background at the detector than a radius 12 mm. Thus a 12 mm radius is chosen, which means the SR fan centroid passes within 7.6 mm of the beamcal edge. This results in a collimation depth of $N_x = 10.5 \ N_y = 66.8$. See Figure 6.
Figure 6. Synchrotron radiation envelope for 2 mrad lattice for a collimation depth of $N_x = 10.5, N_y = 66.8$. The black rectangles illustrate the apertures of the final doublet and the IR beamcals/masks. It can be seen that the exit of the mask after the IP imposes the constraint on the SR fan.

The 2 mrad final doublet was specifically optimised for 500GeV beam energy (see the Appendix for the doublet parameters). The nominal parameters for 500GeV are $\beta_x, y = 30\text{mm}, 0.3\text{mm}, \gamma_{x, y} = 1 \times 10^{-5}\text{m}, 4 \times 10^{-8}\text{m}$, and these were used as the input to the collimation depth calculation. Note the difference to the 20 mrad deck, for which different IP parameters were used.

5 Conclusions

The collimation depths for the 20 mrad and 2 mrad lattices are summarised in Table 1. It should be noted immediately that these are not unique solutions, as is described in Section 2 and that in each case, $N_x$ can be reduced at the expense of increasing $N_y$, and vice-versa.

Table 1. Summary of collimation depth results for the 20 mrad and 2 mrad lattices described in this report.

<table>
<thead>
<tr>
<th>Crossing Angle</th>
<th>L*(m)</th>
<th>IP parameters</th>
<th>Collimation Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 mrad</td>
<td>3.51</td>
<td>250GeV $\beta_{x, y} = 15\text{mm}, 0.4\text{mm},\gamma_{x, y} = 1 \times 10^{-5}\text{m}, 3 \times 10^{-8}\text{m}$</td>
<td>$N_x = 9.6, N_y = 73.9$</td>
</tr>
<tr>
<td>2 mrad</td>
<td>4.50</td>
<td>500GeV $\beta_{x, y} = 30\text{mm}, 0.3\text{mm},\gamma_{x, y} = 1 \times 10^{-5}\text{m}, 4 \times 10^{-8}\text{m}$</td>
<td>$N_x = 10.5, N_y = 66.8$</td>
</tr>
</tbody>
</table>

The collimation depths correspond to spoiler half-gaps of: for 20 mrad 1.07 mm (x) and 0.57 mm (y); for 2 mrad 1.17 mm (x) and 0.52 mm (y).

The difference in the IP parameters between the two designs should be noted. Ideally, for comparative purposes, the same IP parameters should be used for both 20 mrad and 2 mrad
lattice. However, a pair of lattices (20 mrad and 2 mrad) designed to the same IP parameters does not exist.

It is interesting to compare these collimation depth with those obtained for previous designs\textsuperscript{vi}. It may be expected that the results would be similar. For the TESLA lattice \(N_x = 13, N_y = 80\) while the NLC lattice \(N_x = 15, N_y = 30\). The more severe constraint on \(N_y\) in the NLC lattice than is seen here is not understood. The spoiler half-gaps in the NLC design were much tighter, \(\sim 0.3\) mm (x) and \(\sim 0.2\) mm (y), due to the optical design which consisted of consumable spoilers.

These results represent a first estimate of the collimation depths. These studies need to be followed up by accurate particle tracking to determine the effects of energy spread, and non-linear and off-energy transport between the betatron spoilers and the final doublet.

**Appendix. Doublet Parameters for 2 mrad Lattice**

\[
\begin{array}{l}
\text{IP} - \text{D0} - \text{QD0} - \text{D1A0} - \text{SD0} - \text{D1B} - \text{QF1} - \text{D1C} - \text{SF1} \\
\text{D0} : l= 4.5 \\
\text{QD0} : l=2.5, K1= -0.095553608381, r=35\text{mm} \\
\text{D1A0} : l= 1.3299 \\
\text{SD0} : l=3.8, K2= 0.618886670491 , r=80\text{mm} \\
\text{D1B} : l= 3.883 \\
\text{QF1} : l=2.0, K1= 0.040301067219, r=10\text{mm} \\
\text{D1C} : l= 0.56331+0.016 (0.016 for 16 multipoles) \\
\text{SF1} : l=3.8, K2= -0.203314502448, r=110\text{mm} \\
\end{array}
\]

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**References**

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\textsuperscript{iii}LDC documentation at \url{http://www.ilcldc.org/documents/LDC_introduction.pdf}

\textsuperscript{iv}R. Appleby et al. Optics of the ILC Extraction Line for 2 mrad Crossing Angle. EUROTeV-Report-2006-001-1

\textsuperscript{v}Talk given by K. Buesser at the 2005 Linear Collider Workshop. \url{http://www.slac.stanford.edu/xorg/lcd/ipbi/lcws05/buesser_pairs.ppt}

\textsuperscript{vi}A. Drozdhin et al. Comparison of the TESLA, NLC and CLIC Beam Collimation System Performance. Linear Collider Collaboration Tech Notes. LCC-0111