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Linear Collider Collaboration Tech Notes

Monochromatization Option for NLC Collisions

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Abstract: In this note, we consider an option for NLC operation where the Interaction Point beam parameters are adjusted in order to increase the energy resolution. This is achieved by squeezing the horizontal betatron function at the IP and simultaneously introducing a horizontal dispersion (with a different sign for electron and positron beams). While the total horizontal beam size remains constant, the beam is now spread in energy in the horizontal plane so that lower energy particles collide preferentially with higher energy particles. The resulting luminosity spectrum becomes sharper and any possible “energy bias” is reduced by more than a factor of two. This option is viable as long as the energy jitter is smaller than the energy spread, as expected.

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Introduction

One of the techniques used to preserve the beam emittance in a linear collider is to introduce a correlation between energy and longitudinal position in the bunch, such that the bunch head has higher energy than the tail. The lower energy tail is then more strongly focused by the linac quadrupoles, which compensates for the wakefields generated by the bunch head (BNS damping [1]). Figure 1 shows the BNS energy spread for the NLC linac. The correlated energy spread is added at the beginning and then mostly removed during the last 1/3 of the linac. The typical shape of the residual energy-z correlation and the energy distribution at the end of the NLC are shown in Figure 2.

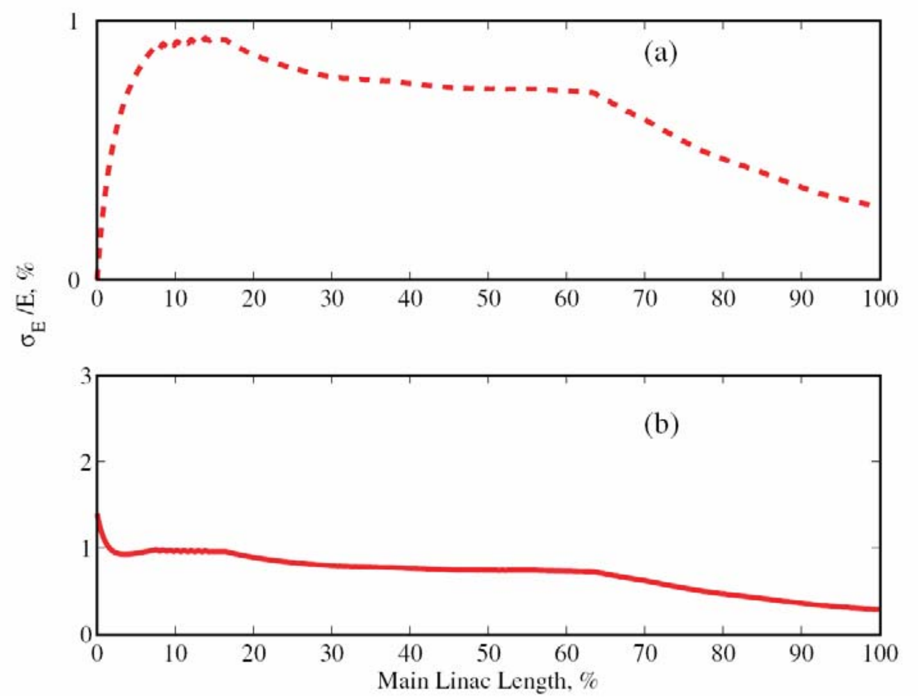

Figure 1. Energy spread in the NLC main linac: (top plot) the correlated BNS energy spread; (bottom plot) total energy spread, including incoming energy spread.

Recent studies [2] have shown that the energy-z correlation in combination with beam-beam effects may cause an error in the determination of the luminosity-weighted center of mass energy. This deviation is called the “energy bias” and was found to vary from several hundred ppm (parts per million) up to about 1000 ppm. Although, from the accelerator physics perspective, this bias could be predicted and compensated for in various ways, it is not directly measurable by Bhabha acolinearity technique* and may complicate the physics analysis. It is therefore desirable to consider ways to mitigate such energy bias for certain physics analyses. In the following, we consider an option of NLC operation that would produce nearly monochromatic collisions and thus reduce any energy bias.

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* For example, the energy spread caused by beamstrahlung is much larger, several thousand ppm. However, there are studies which indicate that it can be measured by using a Bhabha acolinearity analysis [3].

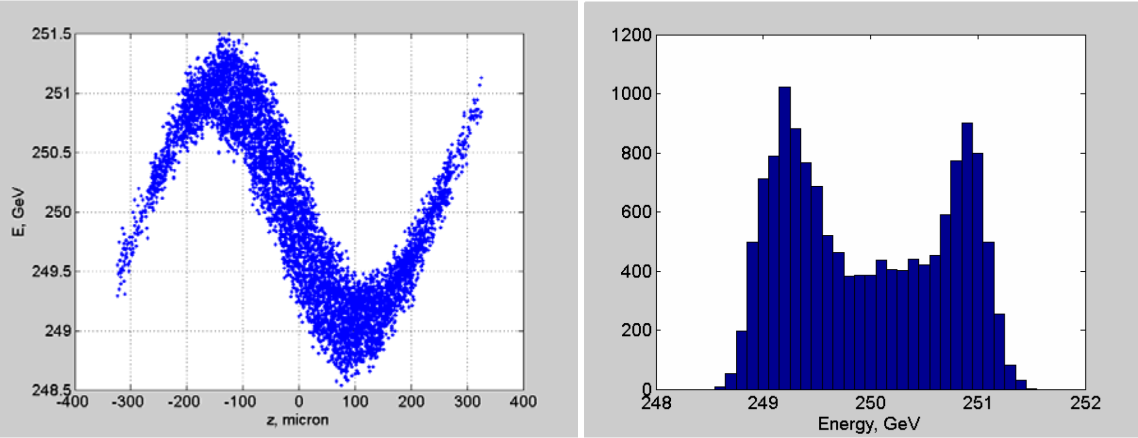

Figure 2. Energy versus longitudinal position in the bunch (left plot) with the bunch head (negative z) having higher energy and the histogram of the energy distribution (right plot) showing the typical “batman shape” for one of the simulated NLC bunches.

Monochromatization of NLC collisions

The concept of monochromatization with asymmetric dispersion was suggested as early as 1975 [4]. It has been extensively discussed in the τ-charm factories proposals, see e.g. [5-7] and was also considered, though without detailed studies, for linear colliders in the JLC-I report [8].

The NLC IP parameters can be modified to have the x-beta function (4mm) half of nominal (8mm) and 58 microns of additional horizontal dispersion at the IP by minor changes in the optics of the Beam Delivery System (discussed further below). The value of the additional dispersion matches the effective rms energy spread in the bunch (~0.3%) so that the effective horizontal beam size is equal to the nominal 243 nm $((243^2 / 2 + (58*3\text{pm})^2)^{0.5} = 243$ nm) and the luminosity is approximately constant.

With these parameters the horizontal betatron beam size at the IP is reduced by a factor of 1.4, while the horizontal beam divergence is increased by a factor of 1.4 and the horizontal angular dispersion is kept constant, and the beam is spread in energy as shown in Figure 3. The additional dispersion in the electron and positron beams is introduced with opposite signs in such a way that high energy particles from one beam collide preferentially with low energy particles of the other beam, providing partial monochromatization of the collisions (see Figure 4).

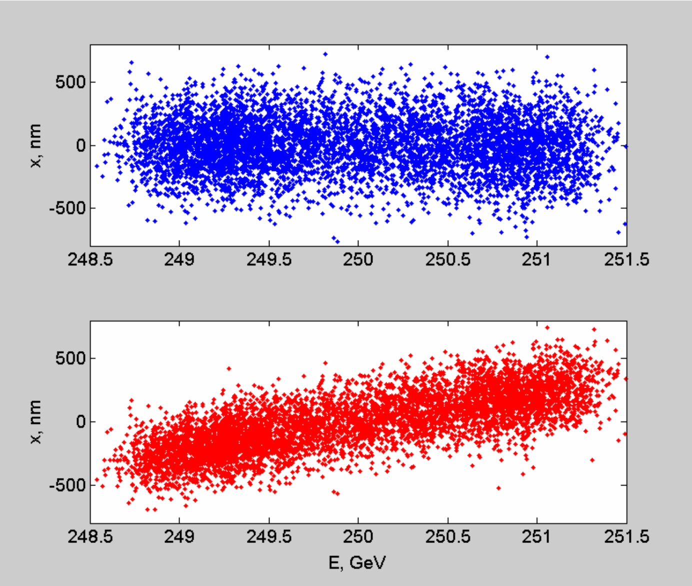

Figure 3. Horizontal position of electrons at the IP versus their energy. Top plot shows the nominal NLC parameters, and the bottom plot shows the beam with squeezed horizontal beta-function and additional horizontal dispersion.

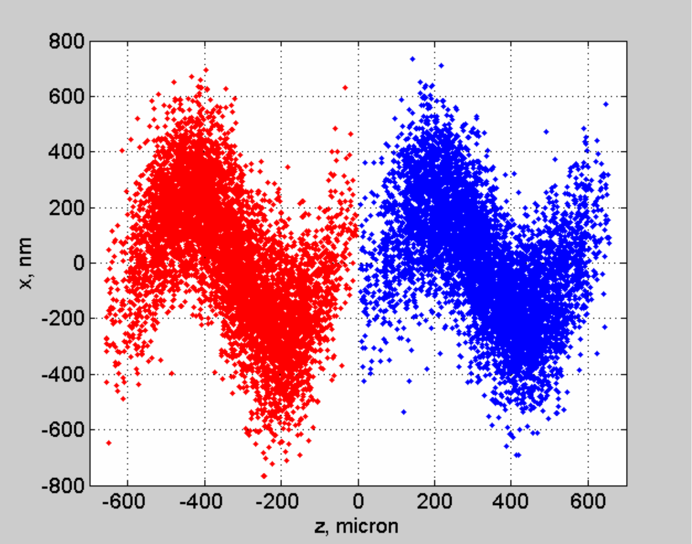

Figure 4. Horizontal and longitudinal positions of electrons and positrons before collision in the monochromatization scheme.

To determine the energy bias, we use realistic (non-ideal) beams at the IP obtained during the TRC studies [9-12] and input them into the beam-beam simulation program GuineaPig [13]. The resulting luminosity events are then analyzed to determine the luminosity-weighted center of mass energy (sqrt(s')). Any deviation from 500 GeV is the energy bias. Examples of the luminosity event distribution versus center of mass energy are shown in Figure 5 for both nominal and modified parameters (beamstrahlung is turned off). For this particular case, Ebias = 572 ppm and L=1.93*10^{34} $cm^{-2}s^{-1}$ for the nominal parameters and Ebias = 301 ppm, L=1.91*10^{34} $cm^{-2}s^{-1}$ for the modified parameters. The rms widths of the distributions are 0.20% for the nominal and 0.135% for the modified case.

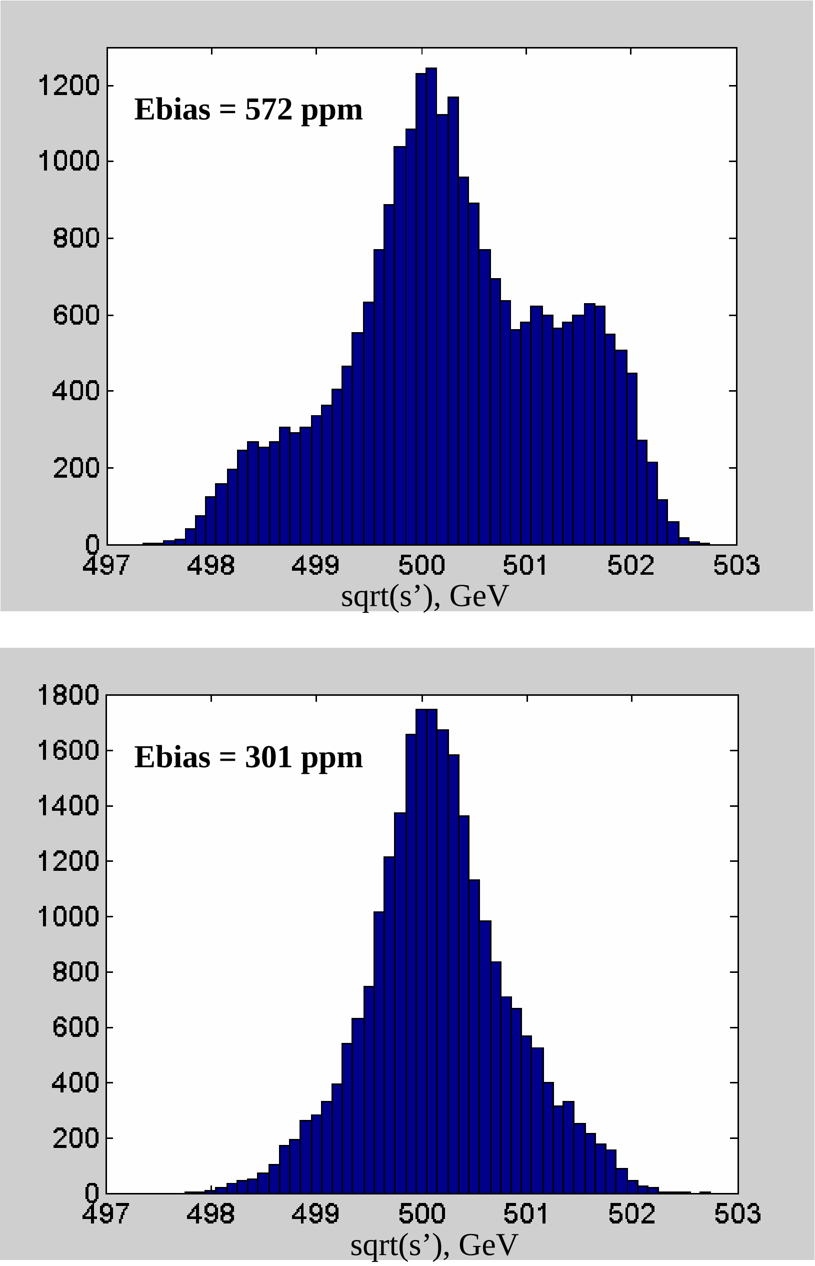

Figure 5. Distribution of luminosity events versus center of mass energy for one particular simulated NLC machine for nominal IP parameters (top plot) and for parameters with monochromatization of collisions (bottom plot).

As we see, the center of mass histogram is now much narrower and more symmetric, and the energy bias is reduced by about a factor of two, with constant luminosity.

Next, we extend this study to one hundred different simulated NLC machines (each of which has different errors and misalignments in the linac and consequently different beam distributions at the IP). The results are shown in Figure 6.

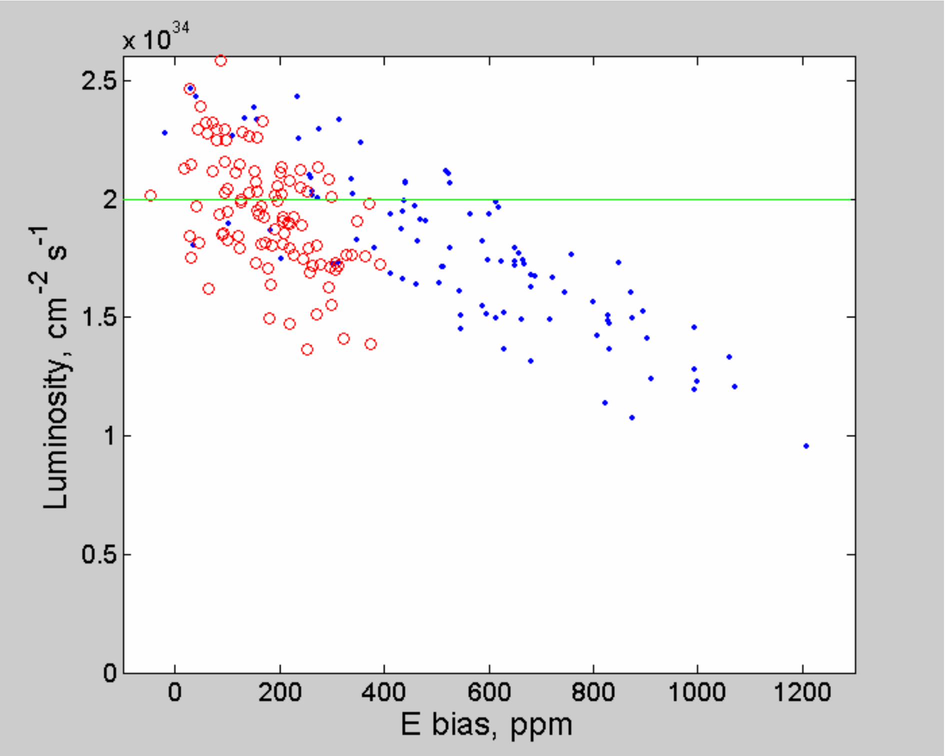

Figure 6. Energy bias for one hundred different simulated NLC machines, nominal IP parameters (blue dots) and IP parameters with monochromatization of collisions (open red circles). The nominal luminosity is shown by green horizontal line.

One can see in Figure 6 that there is a noticeable correlation of the energy bias with luminosity for the nominal IP parameter case, and for the extreme cases (>1000ppm) the luminosity is half of the nominal value. This is an indication that the procedure which generated these simulated machines was overly simplistic. For each case, a simple one-to-one steering algorithm was applied to a randomly misaligned machine[‡]. In real situations, a machine which achieved low luminosity would be tuned using more complex algorithms, until nominal luminosity was achieved. Therefore, such cases should probably be disregarded or given lower weight.

One can see in Figure 6 that for the case with monochromatization the energy bias is reduced by more than a factor of two. While the luminosity scatter is similar, the correlation of the energy bias with luminosity is less pronounced. The corresponding histogram of the energy bias for these one hundred machines is shown in Figure 7. With monochromatization, the mean energy bias is below 200 ppm.

[‡] For the TRC luminosity performance study, only those machines with approximately nominal luminosity were selected from these one hundred machines generated.

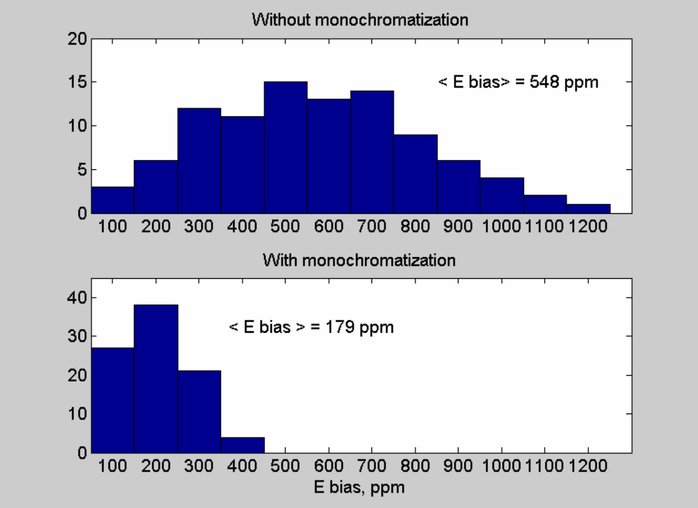

Figure 7. Distribution of the energy bias for one hundred different simulated NLC machines for the nominal (top plot) and modified (bottom plot) IP parameters.

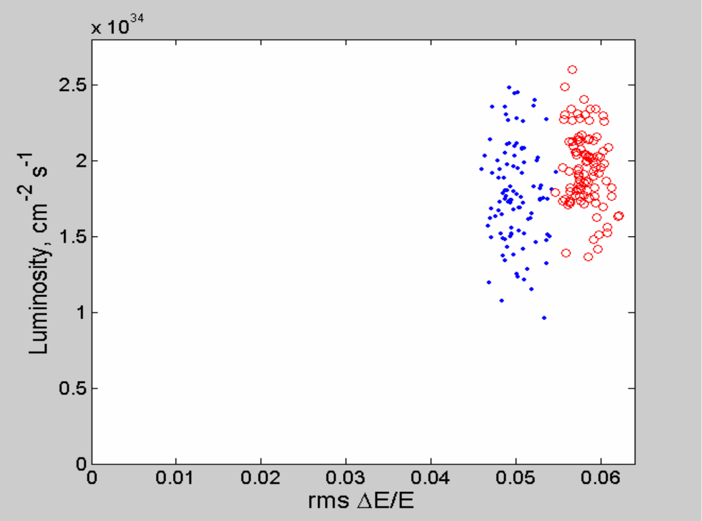

Figure 8. RMS energy loss due to beamstrahlung as a fraction of center of mass energy for 100 simulated NLC machines for the nominal (blue dots) and modified (red open circles) IP parameters.

The change in the IP beam distributions needed to produce monochromatization may also affect other beam-beam effects, such as beamstrahlung. The distribution of the rms center of mass energy loss due to beamstrahlung (which is turned on for this test in Guinea-Pig) is shown in Figure 8. One can see that the energy loss increases by less than a factor of 1.2. As mentioned above, it is assumed that information from the Bhabha acolinearity analysis can be used to characterize the beamstrahlung spectrum, so the increased beamstrahlung is probably not an issue, although this may require further verification[§].

[§] Simulations of the Bhabha acolinearity analysis [3] assumed equal and Gaussian electron and positron beams. In general, we believe that this Bhabha acolinearity analysis should be extended to the case of non-ideal (realistic) and non-identical electron and positron beams, either for the nominal parameters, or for the case with monochromatization.

The width of the horizontal distributions of the outgoing disrupted beam and of the beamstrahlung photons do not increase with the modified parameters, as shown in Figure 9. While the total width of the beamstrahlung photon distribution is unchanged, the left and right asymmetry, naturally caused by asymmetric dispersion, is clearly seen. If this asymmetry caused a problem for the Bhabha acolinearity analysis, the sign of the additional dispersion could be periodically reversed, to zero the asymmetry on average. The vertical outgoing distributions are unchanged, and the average longitudinal position of the luminosity events remains unchanged to within several microns (for considered one hundred files) while the distribution became more rectangular with the modified parameters (see example in Figure 10).

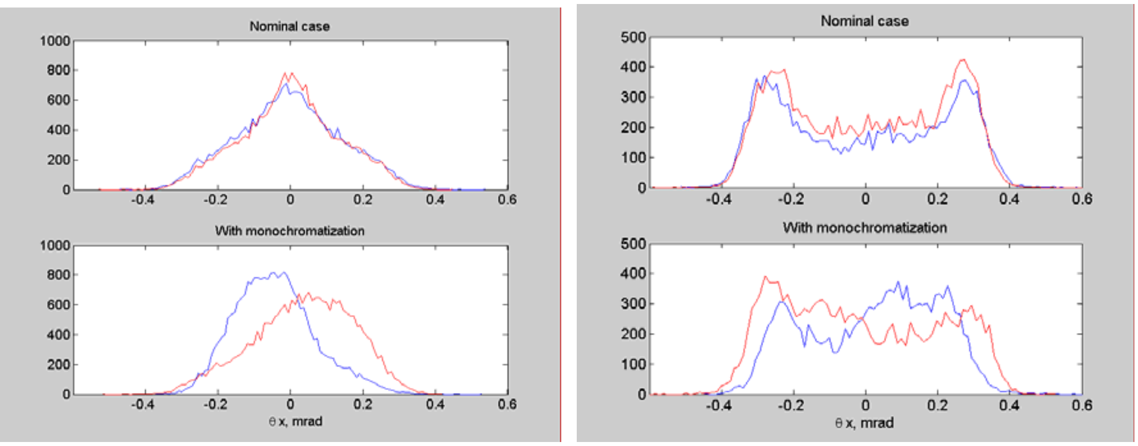

Figure 9. Horizontal angular distribution of the outgoing beamstrahlung photons (left plot) and outgoing beams, nominal case and the case with monochromatization, for one particular simulated NLC machine. The left and right outgoing beams are shown by different curves.

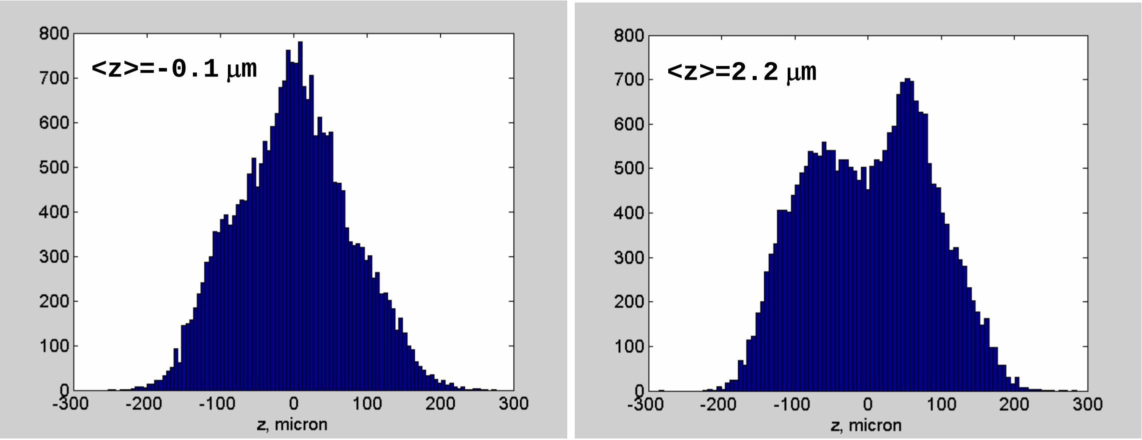

Figure 10. Distribution of luminosity events versus longitudinal position for one particular simulated NLC machine for nominal IP parameters (left plot) and for parameters with monochromatization of collisions (right plot).

It is also worth discussing briefly the feasibility of these monochromatization parameters. This option is viable only if the bunch to bunch energy jitter is smaller than the correlated energy spread in the bunch, as nominally expected from the design. If the energy jitter were too large, it would not be possible to introduce horizontal dispersion at the IP.

Finally, from the optics point of view, squeezing the horizontal beta function and introducing the horizontal dispersion at the IP are minor changes which do not affect the performance of the BDS. Earlier studies have shown that a horizontal beta function as small as 2 mm can be achieved without degradation of the beam quality. The horizontal dispersion would be introduced by normal tuning knobs using appropriate displacement of sextupoles. The 40% higher incoming beam divergence would result in higher synchrotron radiation in the final doublet, which may be noticeable at TeV energies. The larger beam size in the FD would also require correspondingly tighter settings of the horizontal collimators, which should not be an issue since any adverse effects from the collimators (e.g. wakefields from collimators) occur primarily in the vertical plane.

Conclusions

A monochromatization option for NLC operation has been proposed. For this mode, the IP horizontal betatron beam size would be reduced by squeezing the horizontal betatron function by a factor of two and the beam would simultaneously be distributed in energy due to additional horizontal dispersion (with different signs for electron and positron beams). The lower energy particles then preferentially collide with higher energy particles. As a result, the luminosity spectrum becomes sharper and more symmetrical, and the possible “energy bias” is reduced by more than a factor of two. For the simulated machines studied, the bias is on average below 200 ppm. This option is viable as long as the energy jitter is small as designed (0.2%) and if the Bhabha acolinearity analysis or other technique can compensate for the effects of beamstrahlung.

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