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INTENSITY DEPENDENT EFFECTS IN THE ILC BDS

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Abstract

The International Linear Collider (ILC) is an electron-positron collider being considered for the post-LHC era. Its Beam Delivery System (BDS) receives the beam from the main linac. This beam is then focused to the nanometer scale after going through collimators, beam diagnostic systems, strong magnets, etc. Effects such as wakefields due to resistive-wall, BPMs and collimators make the system very sensitive to the beam intensity. Understanding these effects is crucial in order to demonstrate that the nominal beam size at the Interaction Point (IP) can be reached in realistic scenarios. In this paper, results of the intensity dependence effects in the ILC BDS, simulated with PLACET, are presented.

INTRODUCTION

The ILC Final Focus System is based on the local chromaticity correction technique [1] [2]. This system has been tested and is used at the Accelerator Test Facility (ATF2) at KEK [3]. Recent experiments at ATF2 show that the beam intensity deteriorates the quality of the beam and hence increases the beam size at the IP. Indeed, a vertical beam size of 41 nm (compared to nominal goal of 37 nm) was measured in 2016 at 10% of the nominal beam charge of $1.0 \times 10^{10} e^-$. The intensity dependence effects in the ILC BDS is one crucial point to study for future linear colliders. The following simulations will first focus on the impact of realistic machine imperfections and corrections. Then, the impact of wakefields on a train of 1312 consecutive bunches will be presented.

ILC BDS SINGLE-BUNCH SIMULATIONS

The ILC BDS was simulated with PLACET [4], a tracking code which simulates the dynamics of a beam in a linac in the presence of wakefields. It enables the investigation of single- and multi-bunch effects. The latest ILC lattice version was used (31-Dec-2016). The Twiss functions and the ILC BDS main parameters are shown in Fig. 1 and Table 1.

Table 1: ILC Beam Parameters

Parameter	Symbol	Value
Centre-of-mass energy	E_{CM}	500 GeV
Number of bunches	n_b	1312
Bunch population	N	2.0×10^{10}
RMS bunch length	σ_z	0.3 mm
Bunch separation	Δt_b	554 ns
IP RMS beam sizes	σ_x^*/σ_y^*	474/5.9 nm

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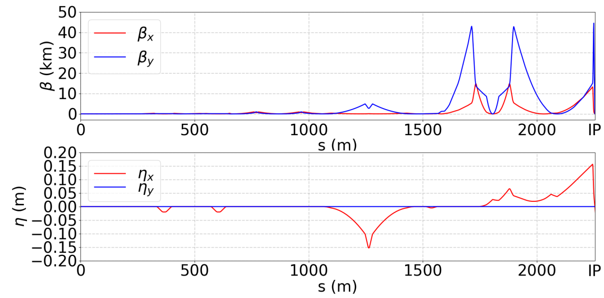

Figure 1: ILC BDS Twiss parameters calculated with PLACET.

The efficiency of the Beam-Based Alignment correction and knobs in the ILC BDS was studied with PLACET. A Gaussian beam made of 2.0×10^{10} electrons and 30000 macro-particles is tracked from the entrance of the ILC BDS to the IP. Each Cavity Beam Position Monitor (CBPM) generates a wakefield kick. The wakepotential of these CBPMs was calculated using Gdfidl [5] and is shown on Fig. 2. Imperfections are taken into account: misalignment and roll error of quadrupoles, CBPMs and sextupoles by respectively 50 µm rms and 200 µrad rms and quadrupole, sextupole strength error of 1.0×10^{-4}. 100 machines were taken into account and the same corrections as in ATF2 are applied: A one-to-one correction that steers the beam and minimizes the transverse displacements measured by BPMs. Then Dispersion-Free Steering is applied, to cancel the unwanted dispersion introduced by misaligned quadrupoles. This correction steers the beam through the center of the BPMs and simultaneously minimizes the difference between the trajectories of two beams with different energies. Another correction is applied, the Wakefield Free Steering correction, which minimizes the difference of orbits between beams with different charges [6]. And finally, tuning knobs are applied at the IP. These knobs remove the correlations between the following couples: $< y, x' >, < y, y' >, < y, E >$ and $< y, x' \times x' >, < y, x' \times y' >< y, x' \times E >$ [7].

The impact of the corrections on the particle distribution at the IP for one machine is shown in Fig. 3. In order to show the impact of each single correction, the particle distributions were centered plotting $Y' - \overline{Y'}$ and $Y - \overline{Y}$. The results of the corrections on the vertical beam size at the IP for 100 machines are summarized in Table 2.
The average vertical IP beam size for 100 machines is decreased after each correction. One-to-one correction does most of the work, then, DFS and WFS make the machine less sensitive to energy and intensity changes, while they decrease the IP beam size. The whole procedure reduces

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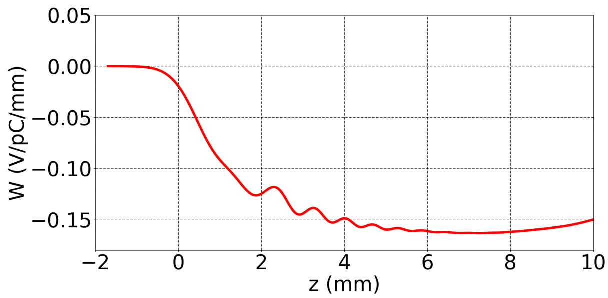

Figure 2: Transverse wakepotential in V/pC/mm calculated with Gdfidl for a vertical offset of 1 mm, Gaussian bunch length of 0.3 mm and 1 pC charge.

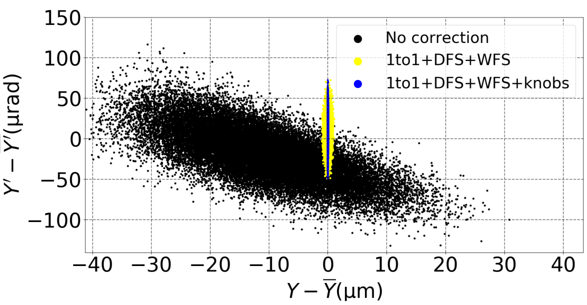

Figure 3: Vertical phase space at the IP of the ILC BDS with imperfections and corrections, calculated with PLACET.

the average vertical IP beam size for 100 machines from 12882 nm without any correction to 6.8 nm. In comparison, the vertical IP beam size in a perfect machine is 5.9 nm. The same simulations were done for a beam with 10% of the nominal intensity. It shows that the growth due to the short-range wakefield in single bunch mode is slight if one considers all CBPMs as wakefield sources. Indeed, the growth between the vertical IP beam size with $2.0 \times 10^9 e^-$ in a bunch and $2.0 \times 10^{10} e^-$ is 0.2 nm, less than 3 %. In reality, a bunch train made of 1312 bunches is traveling in the ILC BDS. Each bunch feels the wakefield created by itself (short-range wakefield) but also generates a long-range wakefield which affects the following bunches.

ILC BDS MULTI-BUNCH SIMULATIONS

In order to study the multi-bunch intensity dependence effects in the ILC BDS, one should consider long-range wakefields such as the ones generated by resistive walls. The ILC BDS copper coated beam pipe has an aperture between 10 mm and 30 mm. The ILC BDS beam aperture profile is shown in Fig. 4. The resistive walls wake function used in the simulations is defined as follows [8]:

$$W_1(z) = -\frac{c}{\pi b^3}\sqrt{\frac{Z_0}{\sigma_r \pi z}}L \qquad (1)$$

where b is the radius of the beam pipe, Z_0 is the impedance of the vacuum, $\sigma_r$the conductivity of the pipe, L the length of the beam line segment. In Fig. 5 is shown the calculated

Table 2: Comparison between the average vertical beam sizes at the IP for 100 machines after the ILC correction procedure and with imperfections.

Correction	$\overline{\sigma_y^*}$ $2 \times 10^9 e^-$	$\overline{\sigma_y^*}$ $2 \times 10^{10} e^-$
No correction	12669 nm	12882 nm
1to1	451 nm	458 nm
1to1 + DFS	354 nm	367 nm
1to1 + DFS + WFS	352 nm	365 nm
1to1 + DFS + WFS + knobs	6.6 nm	6.8 nm

wake function for the ILC BDS resistive walls, considering a copper beam pipe and a beam pipe radius of 1 cm.

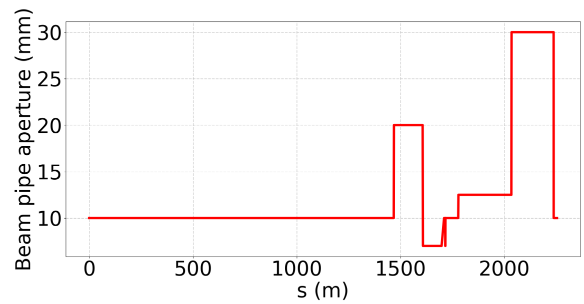

Figure 4: The ILC BDS beam aperture profile.

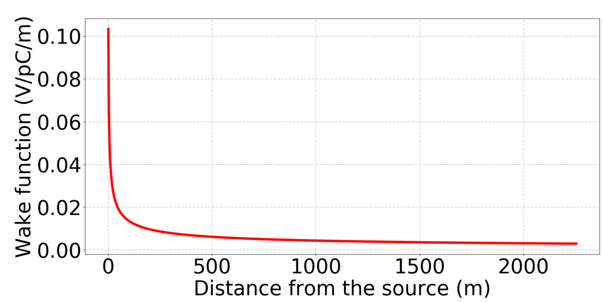

Figure 5: The ILC resistive walls wake function for a copper beam pipe with a constant radius of 1cm.

The effect of the resistive wall effects with PLACET has been simulated using one macro particle per bunch. The consecutive 1312 bunches are injected in a perfectly aligned machine with the same offset. The bunches are tracked all the way to the IP where the orbit of each bunch is calculated. This study is done for initial offsets of $0.1\sigma_y$ and $1.0\sigma_y$ in position and $0.1\sigma_{y'}$ and $1.0\sigma_{y'}$ in angle (where σ_y and $\sigma_{y'}$ are respectively the beam size and beam divergence at the entrance of the BDS). In Fig. 6 is shown the vertical orbit at the IP for the consecutive 1312 bunches at two different beam intensities for incoming position offsets of $0.1\sigma_y$ and $1.0\sigma_y$. The effect is significant, in the vertical case the last bunch gets deflected by 0.755 nm compared to the first bunch for a initial position offset of $1.0\sigma_y$ and by 2.03 nm for an initial angle offset of $1.0\sigma_{y'}$ for beam intensity of $2.0 \times 10^{10} e^-$.

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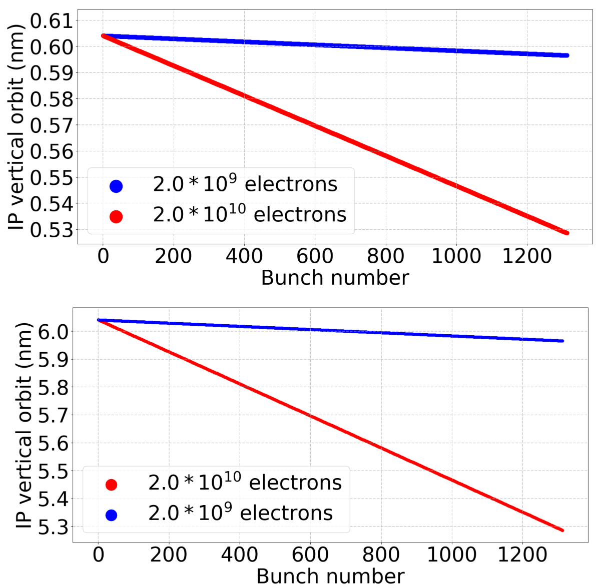

Figure 6: Effects of the resistive walls in ILC BDS on the vertical orbit at the IP with an initial vertical position offset of $0.1\sigma_y$ (top) and $1.0\sigma_y$ (bottom), calculated with PLACET.

These vertical angle and position offsets at the IP also degrade the luminosity significantly. The previous electron bunches are collided at the IP with proton bunches coming from the proton BDS. The resulted luminosity degradation versus the relative offset of the colliding beams is shown in Fig. 7. The results of the impact of resistive walls in ILS BDS on the luminosity are summarized in Table 3. At low beam intensity ($2.0 \times 10^9 e^-$) the impact of an incoming position or angle offset has a negligible impact on the luminosity. However, at high beam intensity ($2.0 \times 10^{10} e^-$), an incoming position offset of $1.0\sigma_y$ leads to a luminosity loss of 3.6% and an incoming angle offset of $1.0\sigma_{y'}$ leads to a luminosity loss of 9.9%. Those results are obtained if no correction is applied. In realty, such a position drift at the IP would be compensated with an intra-train feedback, neutralizing its effects on the luminosity.

Table 3: Impact of different incoming vertical position (Y) and angle (Y') offsets on the relative vertical offset (difference between last and first bunches) at the IP and the luminosity for low and high beam intensities.

Incoming Y	**Intensity**	**Δ_y at IP**	L / L_0
$0.1\sigma_y$	$2.0 \times 10^9 e^-$	0.008 nm	~ 1.0
$0.1\sigma_y$	$2.0 \times 10^{10} e^-$	0.076 nm	0.998
$1.0\sigma_y$	$2.0 \times 10^9 e^-$	0.075 nm	0.998
$1.0\sigma_y$	$2.0 \times 10^{10} e^-$	0.755 nm	0.964
Incoming Y'	**Intensity**	**Δ_y at IP**	L / L_0
$0.1\sigma_{y'}$	$2.0 \times 10^9 e^-$	0.019 nm	~ 1.0
$0.1\sigma_{y'}$	$2.0 \times 10^{10} e^-$	0.20 nm	0.992
$1.0\sigma_{y'}$	$2.0 \times 10^9 e^-$	0.19 nm	0.996
$1.0\sigma_{y'}$	$2.0 \times 10^{10} e^-$	2.03 nm	0.901

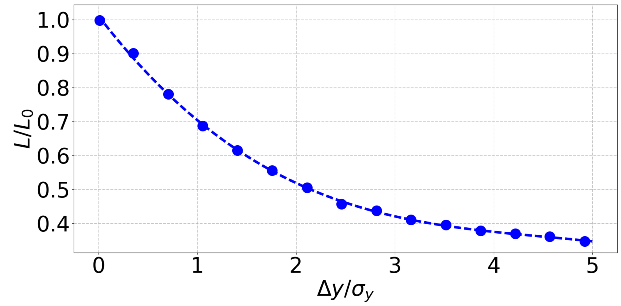

Figure 7: ILC Luminosity degradation vs. relative vertical offset of the colliding beams.

CONCLUSION

PLACET simulations showed that the implemented correction procedure decreases the vertical IP beam size by a factor 1900. These simulations of the ILC BDS also proved that the effects of short-range wakefields on a single-bunch with the tested corrections are relatively small. Indeed, after applying the same corrections used in the ATF2 beamline, the average for 100 machines of the vertical IP beam size of the 0.3 mm long bunch is increased from 6.6 nm (at $2 \times 10^9 e^-$) to 6.8 nm (at $2 \times 10^{10} e^-$). The implemented long-range wakefields due to resistive walls in a perfect machine induce a significant vertical offset at the IP and thus a luminosity degradation. The luminosity loss is 3.6 % considering a train of 1312 bunches with an incoming vertical position offset of $1.0\sigma_y$ and almost 10 % for a train with an incoming angle offset of $1.0\sigma_{y'}$. This luminosity loss can be compensated with appropriate IP intra-train feedback.

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