FAILURES IN THE MAIN LINAC OF THE INTERNATIONAL LINEAR COLLIDER AND THEIR EFFECT ON THE BEAM DELIVERY SYSTEM*

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Abstract

The International Linear Collider (ILC) relies on very high beam powers and very small beam emittances to achieve the ambitious luminosity of 2×10^{34} cm^{-2}s^{-1}. The potential for damage to the accelerator hardware in the event of some machine failure will require a sophisticated machine protection system. The small apertures in the Beam Delivery System (BDS) - specifically the collimators (by definition the smallest apertures in the machine) are particularly critical. Possible failures in the Main Linac of the ILC and their impact on the BDS are studied using the MERLIN C++ library [1]. We show that the machine is safe for at least one bunch in case of one of the described failures; a fast abort system is designed to safely extract the remainder of the bunches in the pulse to a dump. Investigated are phase and voltage shifts of the klystrons, quadrupole and corrector coil failures.

INTRODUCTION

The main goal of the simulations described in this paper is to show that in case of a failure in the ILC Main Linac (ML), beam loss does not destroy any components in the Beam Delivery System (BDS) or in the detector. The smallest aperture of the BDS is defined by several spoilers followed by absorbers (see Fig. 1: SP2 and SP4), which are designed to filter the beam halo. Therefore, the β-functions have their maximum amplitudes ($\beta_x = 1000$ m, $\beta_y = 600$ m) at SP2 and SP4. These spoilers are mainly hit in case of a magnet failure.

In addition, the BDS allows only a small energy variation. Particles being too far off the nominal beam energy will be stopped by an energy collimator (see Fig. 1: SPEX). This is the critical component in case of klystron failures.

All simulations are based on the ILC2006c lattice [3] and the collimator apertures were set according to the values given in [2]. The specifications of the critical collimators and the beam size at these positions are summarised in Table 1.

In general, the simulations were done without scattering i.e. the particles are stopped when they hit a spoiler or any other aperture. For some example cases the results were confirmed with a more detailed model that includes scattering of the primary particles. In these simulations, scattered particles in the BDS were caught by subsequent absorbers and they never reached the interaction point in a way that was hazardous to the detector.

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Table 1: Collimator specifications and nominal beam sizes at the collimators. A titanium alloy is foreseen for the SPEX and the collimators SP1-SP4 will be made of copper. The SPEX parameters allow for an energy spread of $\delta = \frac{\Delta x}{2}/D = 0.33$ %.

name	thickness		aperture			
	mm	rad. l.	$\frac{\Delta x}{\mathrm{mm}}$	$\frac{\Delta y}{\mathrm{mm}}$	$\frac{\Delta x}{\sigma_x}$	$\frac{\Delta y}{\sigma_y}$
SP1	8.6	0.6	0.6	0.5	31	360
SP2	8.6	0.6	0.9	0.5	8.3	56
SP3	8.6	0.6	0.6	0.5	31	360
SP4	8.6	0.6	0.7	0.5	6.4	56
SPEX	35.6	1.0	1.0	0.8	21	53

name	beam size (σ)		dispersion
	σ_x/mm	σ_y/mm	D_x/mm
SP1	0.0196	0.00139	0
SP2	0.109	0.00895	0
SP3	0.0196	0.00139	0
SP4	0.109	0.00895	0
SPEX	0.0482	0.0150	153

When the beam becomes unstable, the details on how and where particles are lost depend on small differences in the linac alignment. We therefore consider a realistic model for an already commissioned, working linac with remaining alignment errors for the cavities and quadrupoles in the Main Linac ($\sigma_{x,y} = 300\ \mu m$) and for the quadrupoles in the Beam Delivery System ($\sigma_{x,y} = 200\ \mu m$).

In this model a 1-to-1 steering algorithm is integrated

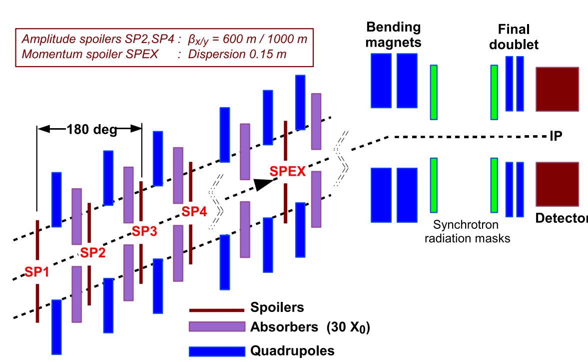

Figure 1: Layout of the ILC Beam Delivery System [2]. Shown are the amplitude spoilers SP1 to SP4 and the energy spoiler SPEX, which are due to their small apertures the critical components in case of magnet and klystron failures.

to set the corrector dipoles in a way that all BPM readings go to zero. There is one BPM-corrector pair at each quadrupole.

KLYSTRON FAILURES

The acceleration in the cavities depends on the voltage V_0 and the RF phase ϕ. The beam will be lost in the BDS if the acceleration deviates from the nominal value. A small energy change will result in a beam loss due to the energy collimation system which is part of the BDS. This has been simulated taking into account the worst case of all klystrons shifting the voltage or phase at the same time in the same direction. The critical element in the case of such a klystron failure is the energy collimator (SPEX), made of a titanium alloy. The case where a beam with a size of $\sim 1000\ \mu\text{m}^2$ hits a titanium spoiler has been simulated previously [4]. Up to a thickness of 2 radiation lengths the spoiler can survive the hit of a single bunch without severe damage. We define dangerous as: bunch spot area $< 1000\mu\text{m}^2 \times N$(lost particles) / $2 \cdot 10^{10}$.

Voltage Shift

The average gradient of the cavities is 31.5 MV/m. The voltage has been varied by ± 1 %. Figure 2 shows the number of particles reaching the interaction point as a function of the relative voltage change. About half of the beam gets lost for a relative voltage change of more than 0.3 %, being completely lost above 0.5 %. This is consitent with the energy spread allowed by the energy collimator (SPEX) in the BDS (given by the aperture dimensions and the design dispersion at the SPEX, see Table 1). In case of a larger or even complete loss, the major part of the beam gets spoiled by the SPEX and stopped in the absorbers behind (tested with simulations including scattering of the primary particles). Here, the size of the beam is broad enough ($\sigma_x \approx 12\mu$m, $\sigma_y \approx 10\mu$m) to be safe for one bunch. A second bunch might already be critical.

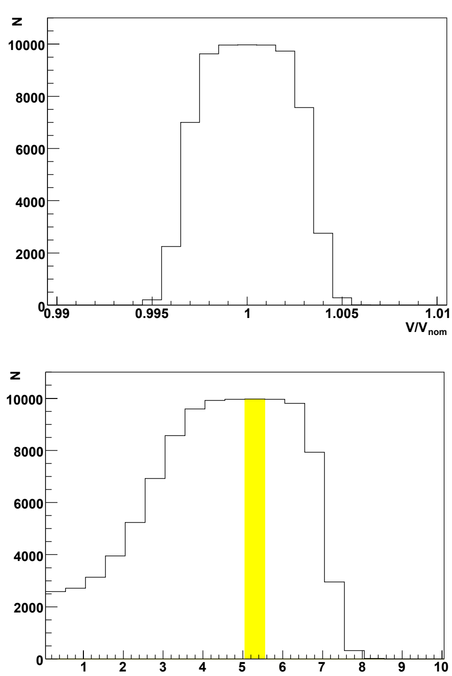

Figure 2: The upper plot shows the number of particles N reaching the interaction point vs. the relative voltage shift. The lower plot shows N vs. the phase shift in degrees. The band indicates the nominal phase. The shapes of the plots are related by the $\cos\phi$ dependency of the accelerating voltage ($V = V_0 \cos\phi$).

Phase Shift

The cavities are operated off-crest with a nominal RF phase of $5.3°$. The phase has been varied from $0.3°$ up to $9.8°$. Figure 2 shows the number of particles reaching the interaction point dependent on the phase shift. About half of the beam gets lost below $3°$ and above $7°$ (compared to a possible shift to $53°$ before the particles get lost in the ML [5]). Similar to the results from the voltage shift simulations, the major part of the particles gets spoiled by the SPEX and stopped completely in the consecutive absorbers.

MAGNET FAILURES

In addition to the cavities, each RF unit contains a quadrupole magnet and combined horizontal and vertical corrector magnets. The maximum gradient required in the quadrupoles at the high energy end of the ML is 60 T/m, while for the corrector dipoles it is about 0.05 T-m [6]. The ILC bunch time structure is essential for the machine protection strategy. The repetition rate is 5 Hz, while the total pulse length is only 969 μs (2625 bunches with a spacing of 369 ns).

A failure of the quadrupoles and of the vertical corrector magnets has been investigated.

Quadrupole Failure

In the BDS, the complete failure of one single ML quadrupole or a corrector coil can lead to a total beam loss.

However, the superconducting magnets have a time constant of more than 1 ms. If the magnet failure occurs during the 200 ms without beam in the ML, the beam must not be extracted from the damping ring. If the quadrupole starts to ramp down during the 1 ms with beam in the ML, not more than 0.04 % of the field will vanish in the time between two bunches ($\approx$ 370 ns).

The effect of a field reduced by 0.04 % is negligible concerning the beam trajectory. The beam is not lost and reaches the interaction point as expected. With decreasing magnetic field, the consecutive bunches will slowly move out of the nominal bunch position. Here, the beam position monitors (BPMs) can give an early warning to the machine protection system to dump the beam.

Table 2: Summary of the beam losses for quadrupole failures with different field strengths. The maximum number of lost particles does not always describe a case with a dangerous loss, as in many cases the beam is too large enough to cause harm. All numbers are given with respect to the 500 simulation runs.

quadrupole field strength	cases with > 10 % loss	max. beam loss per collimator	dangerous due to strong focus
99 %	none	0.4 %	none
95 %	1 %	16.8 %	none
90 %	10 %	99.6 %	4 %
0 %	100 %	99.8 %	10 %

Table 3: Summary of the beam losses for corrector coil failures with different field strengths.

corr. coil field strength	cases with > 10 % loss	max. beam loss per collimator	dangerous due to strong focus
99 %	none	16.9 %	none
95 %	none	41.3 %	none
90 %	8 %	99.7 %	3 %
0 %	88 %	99.8 %	7 %

To study a stronger field decay, the cases of 99 %, 95 %, 90 % and zero remaining field strength are further investigated. One failing quadrupole (here #0, #100, #150, #200, #250) was simulated for 100 different random misalignment scenarios.

If more than 10 % of the beam is lost and the geometric cross-section of the beam is small enough, it is possible that the beam causes damage due to thermal fracture [4]. Therefore, in the analysis of the simulations, for the cases with more than 10% loss, the distribution of the lost particles is fitted assuming a Gaussian distribution. Even with the real distribution not being Gaussian, it was confirmed that the fit gives a reasonable estimate of the beam size. An overview of the results is given in Table 2.

In the dangerous cases with 90 % quadrupole field, the spoilers SP2 (75 %) and SP4 (25 %) are hit. When the magnetic field is completely down, the spoilers SP1 (80 %) and SP3 (20 %) are hit instead.

In the case of a complete failure of one quadrupole magnet, the beam is always lost completely. 10 % of all cases are dangerous due to small beam sizes at the stopping collimator. Here, it is most dangerous if the beam gets lost in the spoilers SP1 and SP3, as the beam has a smaller size here than in the other spoilers that are frequently hit, SP2, SP4 and SPEX (see Table 1).

Corrector Failure

The failure of a corrector coil has a similar effect on the beam as a failing quadrupole. The results for of 5×100 runs (with corrector coils #0, #100, #150, #200, #250 failing) are shown in Table 3.

The dangerous losses with complete magnet failure occur usually at the spoiler SP1.

Table 4: Summary of the beam losses for correlated quadrupole and corrector coil failures with different field strengths.

quad.& corr. coil field strength	cases with > 10 % loss	max. beam loss per collimator	dangerous due to strong focus
99 %	4 %	17.1 %	none
95 %	6 %	80.5 %	none
90 %	17 %	99.7 %	2 %
0 %	100 %	99.7 %	15 %

Combined Failure of Quadrupole and Corrector

As the corrector is foreseen to compensate the dipole error of the quadrupole, it might be expected that in case of a failure of both magnets the effect is less severe. Table 4 shows that this is not the case. Again, 5×100 simulations (with quadrupole and corrector coils #0, #00, #150, #200, #250 failing) have been analysed. With the magnetic field at 90 %, dangerous losses occur usually at SP2. In 2/3 of the dangerous cases with zero magnetic field, the beam got lost in SP1, in all other cases in SP3.

SUMMARY

In the ILC beam delivery system (BDS), half of the beam will be lost when the RF phase is below 3° or above 7°. The BDS is safe for one bunch only, so that a fast abort system is essential.

A single quadrupole or corrector coil failure will cause a complete beam loss in the BDS. As this failure might cause damage in the BDS with one bunch, the machine protection system has to identify such a failure before the strength of the magnet drops to less than 95 % of the nominal value. As the time-constant of these magnets is large (in the order of ms), this is well possible.

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