FAILURE MODES AND BEAM LOSSES STUDIES IN ILC BUNCH COMPRESSORS AND MAIN LINAC*

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Abstract

Proposed International linear collider (ILC) involves high average beam power. Dealing with high average beam power and smaller beam sizes result in stringent tolerances on beam losses and therefore, extensive studies are required to investigate every possible scenarios that lead to beam losses. In this paper we discuss beam losses due to failure of critical elements in beamline for ILC bunch compressors and main linac.

INTRODUCTION

The ILC [1] is a proposed electron-positron linear (linac) collider with nominal center of mass energy (E_{cm}) in range of 250-500 GeV. It would deliver a beam pulse containing 1312 bunches (N_B) with $2\text{x}10^{10}$ particles per bunch (n_p) at repetition rate (f_{rep}) of 5Hz. Thus, average beam power (P) estimated using equation (1) is about 5MW.

$$P = n_p N_B f_{rep} E_{CM}; \tag{1}$$

As shown in equation (2), luminosity (L) is inversely proportional to the transverse RMS beam sizes (σ_x, σ_y). Thus, in order to achieve high luminosity ILC would deliver a beam with smaller RMS size < 100 μm.

$$L \approx \frac{n^2{}_p N_B}{4\pi\sigma_x\sigma_y} f_{rep}; \tag{2}$$

Involvement of high average beam power and small beam size and therefore, high charge density results in stringent tolerances on beam losses. Consequences of high beam losses are very severe in ILC like superconducting accelerators. High beam losses could result in radio-activation and therefore interrupt hands on maintenance. In some worst cases localized beam losses could lead to melting of element's surface resulting its destruction. Replacing of elements in the cryogenic environment takes a long time leading to the unscheduled beam interruptions. Thus, a detailed study is required to understand every possible beam losses scenarios and to quantify in terms of their severity. This knowledge will facilitate in preparing an advanced machine protection system (MPS) that will protect the machine from any potential damage and will assist the machine to operate in fail-safe mode. In this paper we discuss potential beam loss mechanisms in ILC linac and assess them in terms of their severity.

* Work supported by Fermi Research Alliance, LLC under Contracts No. De-Ac02-07CH11359 with the DOE, USA.
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FAILURES OF CRITICAL COMPONENTS

Total length of ILC is more than 30 km and it is composed of several thousands of beamline elements. Continuous operation of those elements in pulse mode increases the possibility of their failure. Failure of a quadrupole magnet will change transverse focusing period of the beam. It will result in a beam mismatch with subsequent sections and eventually beam losses. Similarly a malfunctioned accelerating cavity will cause mismatch in energy with subsequent sections. Failures of elements in beamline can be placed in two categories, temporary failures and permanent failures. As name suggests, temporary failures are recoverable after applying appropriate mitigation scheme. On the basis of recovery time, temporary failures are further divided into two categories i.e. fast failures that are recovered at the time scale of microsecond and slow failures that are recovered within milliseconds. An abrupt jump in operating phase of the cavity will result in a fast failure. Quench of superconducting cavities, power trip, and vacuum breakdown leads to slow failures. Impacts of fast failures are on bunches in a pulse while implications of slow failures are distributed among pulses. All the beam pulses get affected from the permanent failures of beam-line elements. Thus, failures of critical components in beam-line are major source of beam losses. In subsequent sections we studies failure modes in ILC bunch compressors and main linac.

FAILURE MODES IN BUNCH COMPRESSORS

ILC deploys two stage bunch compression scheme to deliver ultra-short bunches to the main linac. First stage of bunch compressor (BC1) consists of three cryomodules. BC1 is followed by second stage of bunch compressor (BC2) which is composed of 16 RF units. Each RF unit consists of three cryomodolues. Beam energy at entrance and exit of BC1 is 5 and 4.86 GeV respectively. Beam energy at the end of BC2 is 14.83 GeV. Initial bunch length at the BC1 is 6 mm while bunch length at the exit of BC1 and BC2 is 0.9mm and 0.32 μm respectively.

RF Phase Errors in Bunch Compressors

Operating RF phases and gradients in cavities at BC1 are -115^0 and 18.7 MV/m respectively and at BC2 they are -24^0 and 25.5 respectively. A change in operating parameters of the cavities will deviate beam energy from its design value. Consequently, there will be mismatch in following dispersive wiggler section. Furthermore, variating in operating phases may also introduce non-linearity in longitudinal phase space. Thus, these changes in nominal operating parameters not only limit possible minimum bunch length that could be obtained in bunch compressor but eventually result in beam losses.

A potential source of phase error in beam line is malfunctioning of master clock. The reference timing signals are generated using a master clock and therefore, offset or failure of this system will result in timing error between beam arrival and RF fields in cavity. Furthermore, failure of LLRF phase amplitude control system also leads to coherent phase shifts in cavities. In order to understand sensitivity of bunch compressor against phase errors, studies are performed to evaluate RF phase acceptance for BC1 and BC2.

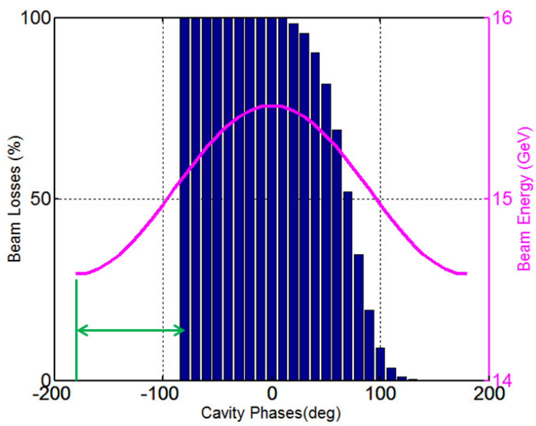
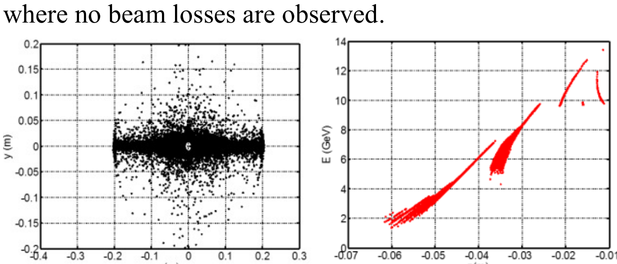


Figure 1: Distribution of beam losses with variation in operating RF phases of cavities in BC1.

To estimate phase acceptance of BC1, beam is tracked through BC1 and BC2. RF phases in all cavities at BC1 are varied from -180^0 to 180^0. However, nominal phases are used in cavities at BC2. Figure 1 shows distribution of beam losses after performing phase scan in BC1. One can notice beam losses for the phases ranging from -90^0 to 120^0. A green arrow points out phase acceptance regime where no beam losses are observed.



(a) (b)

Figure 2: (a) Horizontal and vertical beam size distribution and (b) a zoomed view of longitudinal phase space at the end of BC2 for the case when all cavities in BC1 operate at crest (0^0 RF phase).

In order to investigate nature of beam losses, we studied a case when complete beam is lost along bunch compressor. Figure 2(a) shows transverse beam size distribution of lost beam. It can be noticed that beam transverse sizes are very large ranging -20 cm to 20 cm in both horizontal and vertical direction. Figure 2(b) shows longitudinal phase space of the beam. It can be observed that particles energy vary from 2 to14GeV. Bunch size is ranging from 60 mm to 10 mm. This beam distribution suggests a hollow beam which implies that beam losses are scattered in beamline. Consequently, deposited energy density is low that reduced the possibility of significant damage of beamline elements. Similar study is performed for BC2 to evaluate its RF phase acceptance. All the cavities in BC1 are operated at nominal phases while phases are scanned from -115^0 to 115^0 in BC2. It can be observed from figure 3 that phase acceptance of cavities in BC2 is ranging from -40^0 to 40^0.

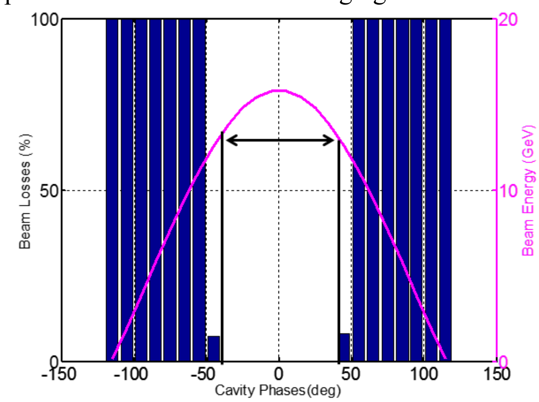
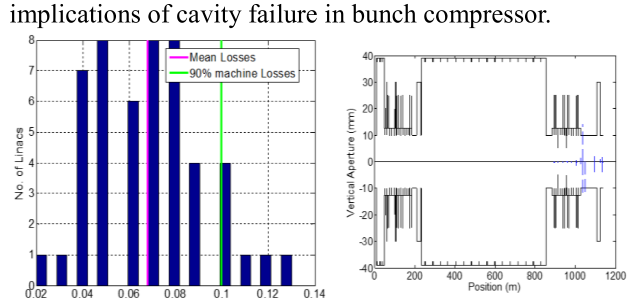


Figure 3: Distribution of beam losses with variation in operating RF phases of cavities in BC2.

Failures of Accelerating Cavities:

Power trip, quenching, failure of low level RF control system, failure of auxiliary components such as power coupler, tuners and excessive field emission are common situations that interrupt nominal operation of the accelerating superconducting cavity. A study is performed to evaluate implications of cavity failure in bunch compressor.



(a) (b)

Figure 4: (a) Distribution of beam losses and (b) vertical aperture profile in bunch compressor. Beam losses are shown using vertical blue lines.

Figure 4(a) shows the distribution of beam losses in perfectly aligned linac for the case when 15 cavities are failed in BC1. It can be observed that even for worst machine beam losses are less than 0.15 %. Location of beam losses are shown in figure 4(b). Beam losses occur at the quadrupoles located in the end of BC2. However, after including misalignment errors as specified in table 1, beam losses increases significantly. It is because of fact that a misaligned quadrupole generates a steering kick. Magnitude of kick is inversely proportional to particle energy. In presence of failed cavities, beam energy is lower than design energy and therefore, beam received even a stronger kick from a misaligned quadrupole that eventually leads to beam

ISBN 978-3-95450-147-2

losses. One to one steering scheme is applied to correct beam centroid trajectory. Figure 5 shows distribution of mean losses with number of failed cavities for three cases i.e. failed cavities in perfectly aligned beamline, failed cavities in misaligned beamline, and failed cavities in misaligned beamline with correction. It can be observed from figure 5 that beam losses are negligible even after failures of significant number of cavities. However, beam losses increases substantially after including misalignments errors. One to One steering brings them back to lower level.

Table 1: Misalignment Tolerances in Bunch Compressor

Source	Amplitude
Cavity Offset	300µm
Quadrupole Offset	300µm
Quadrupole Tilt	300µrad
Cavity Tilt	300µrad
Cryomodule Offset	200µm
Cryomodule Tilt	35µrad
BPM Offset	300µm

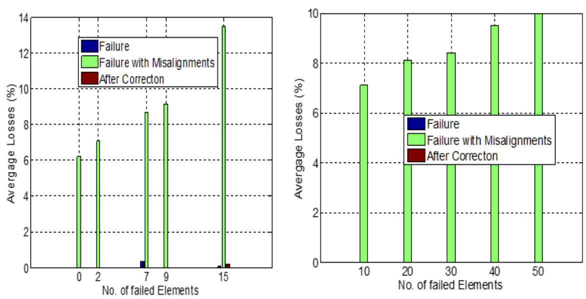


Figure 5: Average beam losses with failed cavities in BC1 (left) and BC2 (right) for different cases.

Quadrupole Failure

Potential sources of quadrupole failures are quenching of superconducting quadrupoles, breaking of magnetic coils and power supply trip.

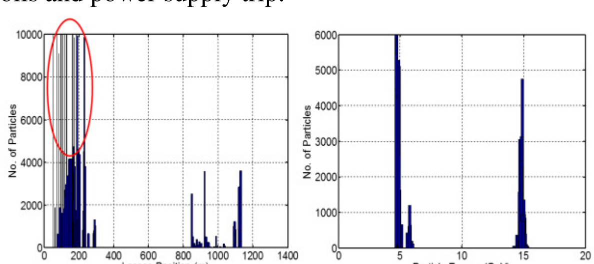


Figure 6: Location (left) and energy (right) distribution of beam losses in bunch compressor after failure of five quadrupoles at random locations in BC1.

Figure 6 shows distribution of beam losses and their energy in presence of failure of five random quadrupoles in BC1. Nominal misalignment errors were also included. Most of the beam losses occur at wiggler sections in BC1 and BC2 around energy of 5GeV and 15 GeV. Figure 7 shows distribution of mean losses with number of failed quadrupoles in BC1 and BC2. It can be observed from figure that single quadrupole failure alone (no misalignment) does not contribute to beam losses. Beam losses increases after inclusion of errors. One to one steering assists to reduced beam losses but becomes less effective as number of failure incidents increase.

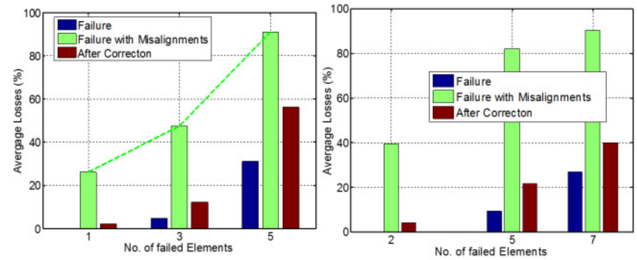


Figure 7: Distribution of average beam losses with no. of failed quadrupoles in BC1 (left) and BC2 (right).

FAILURES MODES IN MAIN LINAC

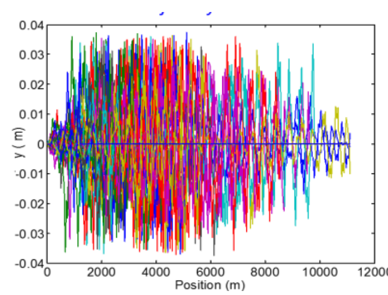


Figure 8: Vertical beam trajectories in main linac for all machines after failure of 18 quads.

Failure modes are studied in main linac using same approach as discussed in earlier section. It is observed that main linac is robust enough to deal with failure of large number of cavities. No beam loss is noticed even failure of 1500 cavities in a misaligned linac. Resulting mean loss after failure of five quads is about 60 %. However, quads failure results in transverse beam oscillation with large amplitude that helps to reduce beam density at impact location. Figure 8 shows vertical beam trajectories for all machines after failures of 18 quadrupoles. Misalignment errors were also included in this study.

CONCLUSION

A detailed study has been performed to understand failure modes and resulting beam losses in ILC bunch compressor and main linac. Failure of quadrupole magnets results in significant beam losses. However, beam losses are scattered and therefore beam density is lower at impact locations.

REFERENCES

[1] C. Adolphsen, M. Barone, B. Barish et al., “The International Linear Collider Technical Design Report-Volume 3.1: Accelerator R&D”.