Overview of Low Emittance Transport and Beam Dynamics Studies of ILC Linac

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Outline

• Introduction
• ILC Main Linac
• Review of Emittance Dilution Mechanisms
  – Baseline Optics
  – Static Misalignments
  – Coupler RF and Wake Kick
• Failure modes
• Summary
Linear Colliders for Higgs Factory

- Snowmass’21 Accelerator Frontier group listed four promising traditional electron-positron collider projects for Higgs Factories.

<table>
<thead>
<tr>
<th></th>
<th>CME (TeV)</th>
<th>Lumi per IP @ Higgs (10^34)</th>
<th>Pre-Project R&amp;D Years</th>
<th>Years to 1st Physics</th>
<th>Cost Range (2021 $B)</th>
<th>Electric Power MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILC</td>
<td>0.25</td>
<td>2.7</td>
<td>0-2</td>
<td>&lt; 12</td>
<td>7-12</td>
<td>140</td>
</tr>
<tr>
<td>CLIC</td>
<td>0.38</td>
<td>2.3</td>
<td>0-2</td>
<td>13-18</td>
<td>7-12</td>
<td>110</td>
</tr>
<tr>
<td>CCC</td>
<td>0.25</td>
<td>1.3</td>
<td>3-5</td>
<td>13-18</td>
<td>7-12</td>
<td>150</td>
</tr>
<tr>
<td>HELEN</td>
<td>0.25</td>
<td>1.4</td>
<td>5-10</td>
<td>13-18</td>
<td>7-12</td>
<td>110</td>
</tr>
</tbody>
</table>

- Integrated Luminosity $\propto \frac{n_b N^2 f_{rep}}{\sigma_x \sigma_y} \times \frac{1}{2} \times \text{Effective Ops. Time}$

- Creative solutions and mitigation strategies developed for ILC are applicable and scalable to new accelerator
ILC Schematic

Ring to Main Linac (RTML)
Polarised positron source
Damping Rings
Polarised electron source
Beam Delivery System (BDS) & physics detectors
Beam dump
e- Main Linac (incl. bunch compressor)

<table>
<thead>
<tr>
<th>Component</th>
<th>Length (500 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length</td>
<td>30.5 km</td>
</tr>
<tr>
<td>SCRF ML (RTML)</td>
<td>22.2 km</td>
</tr>
<tr>
<td>RTML_BC</td>
<td>2.8 km</td>
</tr>
<tr>
<td>Positron source</td>
<td>1.1 km</td>
</tr>
<tr>
<td>BDS / IR</td>
<td>4.5 km</td>
</tr>
<tr>
<td>Damping Rings</td>
<td>3.2 km</td>
</tr>
</tbody>
</table>
**Main Linac Architecture**

- ILC utilizes two types of CMs. Type A comprise nine, 1.3 GHz, 9-cell SRF cavities while Type B includes 8 cavities and a quadrupole magnet package at the center.

  - Arrangement of CMs in configuration of A-B-A makes an RF/ML unit. A total of 285 (282) units for e-linac (e+ linac).
  - Three ML units with cold box makes a cryo-string.
  - Periodic arrangement of cryo-string is interrupted by insertion of 7.7 m warm section.

- Number of cryo strings between successive warm section makes a cryo-unit.
ILC Main Linac Optics

- Maximum periodic Twiss function in horizontal and vertical plane are 120 and 140m respectively.
- Minimum periodic Twiss function in horizontal and vertical plane are 31 and 40m respectively.

Beta Functions in First Cryo-Unit

- ILC2016x (Dec. 2016)
**Curved ILC Linac**

- An essential feature of the ILC Linac is that it follows the earth’s curvature.

- Vertical dipole correctors are used to steer the beam along Earth’s curvature.
- Because there is only one corrector per RF unit (3 cryomodules), beam is steered in such a way that it is passed off-axis through cryomodule but through the center of quadrupoles.

![Optimized Dispersion function](image-url)
Emittance Growth in Baseline Linac

- Beam tracking studies is performed using LUCRETIA
- A Gaussian distribution of 10k macro particles distributed in $4\sigma$ are tracked through the lattice.
- Linac is aligned and wake fields are included

Unmatched Optics

![Graph showing RMS Normalized Vertical Emittance](image)

Matching b/w cryo-units

![Graph showing Matching b/w cryo-units](image)
Main Linac Performance with Static misalignments

Nominal Alignment Tolerances for ILC Main Linac

<table>
<thead>
<tr>
<th>Tolerance</th>
<th>Vertical (y) plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPM Offset w.r.t. Cryomodule</td>
<td>300 $\mu$m</td>
</tr>
<tr>
<td>Quad offset w.r.t. Cryomodule</td>
<td>300 $\mu$m</td>
</tr>
<tr>
<td>Quad Rotation w.r.t. Cryomodule</td>
<td>300 $\mu$rad</td>
</tr>
<tr>
<td>Cavity Offset w.r.t. Cryomodule</td>
<td>300 $\mu$m</td>
</tr>
<tr>
<td>Cryostat Offset w.r.t. Survey Line</td>
<td>200 $\mu$m</td>
</tr>
<tr>
<td>Cavity Pitch w.r.t. Cryomodule</td>
<td>300 $\mu$rad</td>
</tr>
<tr>
<td>Cryostat Pitch w.r.t. Survey Line</td>
<td>20 $\mu$rad</td>
</tr>
<tr>
<td>BPM Resolution</td>
<td>1.0 $\mu$m</td>
</tr>
</tbody>
</table>

- Misalignments were applied only in vertical plane.
- Short range wake fields were included in analysis.
- One to one steering and dispersion free steering were applied in tandem.
Misalignment Implementation

• Random misalignments of individual beamline elements were introduced within the range of +/- $3\sigma$
• Study was performed with 50 machines.

• Distribution of quadrupole, cavity and BPMs offset.
Low Emittance Transport Studies for Curved Linac (1)

**Emittance growth without and with correction**

- Maximum normalized RMS Emittance without correction is \(~2E+06\) nm.
- After applying correction, max. emittance dilution is limited to 12 nm.
- Mean emittance growth after applying correction is 3.3nm.
Low Emittance Transport Studies for Curved Linac (2)

- Distribution of emittance dilution after applying one to one and dispersion free steering.
  - $\Delta \varepsilon = \varepsilon_f - \varepsilon_i$
- 50 machines are used.
- Initial emittance is 24 nm.
- Mean emittance growth after applying correction is 3.3 nm while 90% emittance is 6.7 nm.
• Maximum excursion of beam trajectory without correction is 30mm.
• Superconducting cavity aperture limitation is 35 mm.
• After applying one to one and DFS correction, excursion of beam trajectories are limited in +/- 3 $\sigma$ of BPMs offset.
**Low Emittance Transport Studies for Curved Linac (4)**

- **Mean Emittance Growth for 50 seeds**

**After One to One**

**After One to One +DFS**

- Emittance dilution in curved linac and straight linac after applying correction is within budget of 4 nm dilution (Specification of 20% emittance growth in main linac).
  - Dilution in curved linac is ~2nm higher in comparison to straight linac.
New Realistic Model for Static Misalignment Studies

- Different stages of assembly, installation and commissioning introduce a kind of systematic correlated misalignments among beamline elements in comparison to random misalignments of individual elements.

- Installation of SRF cavities on a string introduces independent random misalignments of the cavity.

- Installation of the string on cryomodule would introduce the string misalignments instead of individual cavity. All cavity on the string would acquire a common offset.
Correlated Misalignment Model

- Cavities misalignment on string
- String misalignment on CM
- CM misalignment on Network Line
- Implications of Correlated misalignments are more severe

Detailed discussion of the model is presented elsewhere:
A. Saini, IPAC 2016, WEPMR012
Misalignment Budget for LCLS-II SRF Linac

- **Correlated Misalignments Budget**

  ![Table I. A budget of alignment tolerances of the LCLS-II linac at different stages of development](chart)

  **Type** | **Reference** | **Amplitude** | **Pattern** | **Distribution**
  --- | --- | --- | --- | ---
  Element assembly on string | String axis | 75μm | Independent | Gaussian
  String assembly on cryostat | Cryomodule axis | 150μm | Independent | Gaussian
  Cryomodule Transportation | Cryomodule axis | 300μm | 3m of string | Gaussian
  Cryomodule Cool-down | Cryomodule axis | 175μm | 3m of string | Gaussian
  Cryomodule Installation | Network line | 50μm | 12m | Gaussian
  Network Alignment | Ideal survey line | 300μm | 100m | Wave-type

- **LCLS-II Independent Random Misalignments Budget**

  ![Tolerance Table](chart)

  | **Tolerance** | **Vertical (y) plane** |
  --- | --- |
  BPM Offset w.r.t. Cryomodule | 500 μm |
  Quad offset w.r.t. Cryomodule | 500 μm |
  Cavity Offset w.r.t. Cryomodule | 500 μm |
  Cryostat Offset w.r.t. Survey Line | 500 μm |
  Cavity Pitch w.r.t. Cryomodule | 500 μrad |
  Cryostat Pitch w.r.t. Survey Line | 50 μrad |
  BPM Resolution | 10.0 μm |
Mean emittance growth comparison

Mean emittance growth after one to one steering

• Mean Emittance dilutions in case of correlated misalignments are ~55% and ~2.7% without and with 1-1 correction respectively.
• Mean Emittance dilutions in case of uncorrelated misalignments are 19% and 1.0% without and with correction respectively.
Coupler RF kick and Wake Kick

- The coupler generates RF and wake kicks
  - Even beam passing through axis experience its kicks

- The kick is dependent on the particle position in bunch.
- Longer bunch has larger impact. One to one steering is not enough for compensation.

Study of Coupler's effect in ILC like lattice, IPAC10, THPD088, A.Saini et al

<table>
<thead>
<tr>
<th>Emittance dilution (nm) due to couplers kicks</th>
<th>Total rf kick</th>
<th>After 1:1</th>
<th>Coupler Wake</th>
<th>After 1:1</th>
<th>Rf kick +wake</th>
<th>After 1:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total rf kick</td>
<td>42.66</td>
<td>0.12</td>
<td>0.38</td>
<td>0.32</td>
<td>45.31</td>
<td>0.48</td>
</tr>
<tr>
<td>After 1:1</td>
<td>42.15</td>
<td>0.22</td>
<td>0.33</td>
<td>0.30</td>
<td>46.38</td>
<td>0.87</td>
</tr>
<tr>
<td>Coupler Wake</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.74</td>
<td></td>
</tr>
<tr>
<td>After 1:1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Bunch Compressor

- RF Kick: 74.46  68.75
- Wake Kick: 3.26  2.91
- RF +Wake: 85.33  79.34
- Girder kick: 2.88  2.22
Fault Scenarios in ILC Linac

• A large number of beamline elements in the linac increases likelihood of a beamline element failure during operation.
• These failures might degrade beam quality, as well as, results in beam loss. Beam loss can be segmented in two categories:
• Unlocalized beam loss: Fractional particle losses over a length for a period of time. Implications are
  – Additional heat load in cryogenic environment
  – Radioactivation
• Localized beam loss: A full bunch or a complete beam pulse is lost on a localized surface.
  – Sever beam induced thermal damage.

Single pulse damage in 1.4mm Cu: NLC studies

M. Ross
http://indico.cern.ch/conferenceDisplay.py?confId=185561
Risk of Thermal Damage in ILC main Linac

- Beam induced thermal damage depends on beam density at impact location
  \[ \Delta T = \frac{1}{\varrho C_m} \left( \frac{dE}{dz} \right) \cdot \sigma_{\text{beam}} \]

- If critical charge density above \( \sim 1 \text{pC/\mu m}^2 \) there is substantial risk of beam induced damage.

- Localized beam loss could result in significant damage in main linac.
  - Understanding of Impact of component failures at vulnerable locations is important to devise appropriate mitigation scheme and Machine protection system

\[ P_{\text{Beam}}^{\text{ILC}} = n_{\text{bunch}} N_{\text{bunch}} f_{\text{rep}} E_{\text{cm}} \approx 5 \text{ MW} \]
Failure Mode Studies for ILC Main Linac

- An extensive study was performed to understand beam sensitivity against a variety of fault scenarios. A. Saini et al, THPMR003, IPAC16
- The main linac is robust against SRF cavity failure.
- Random 5 quadrupole failures in main linac would start generating beam loss.
Quadrupole Failure in Main Linac

• Quadrupole failures alter transverse focusing period and results in large amplitude beam oscillation.
  – Resulting increase in beam sizes reduces beam density at impact location.

Vertical Trajectory distribution for all seeds for a case study for 100% beam loss

Loss Particle Energy Distribution
Failure Modes in Bunch Compressor

- Fault scenarios were also studied in bunch compressors.
- Beam is relatively more sensitive to component failure in bunch compressor.
  - In comparison to main linac, RF phase acceptance in BC1 is lower.
  - Collimators imposes limiting aperture in bunch compressors.

Beam loss with RF phase shift in BC1

Loss Particle in Bunch Compressor
Machine Availability and Reliability

- Availability and reliability engineering aspects need to be incorporated in the design of modern accelerator facilities.
  - Identify potential vulnerable components and develop potential mitigation strategies.
  - Reduce unscheduled beam interruptions
  - Minimize maintenance and operation cost of the machine
- ILC needs an updated machine availability analysis
  - Expertise and experience gained with modern accelerators (XFEL, LCLS-II) needs to be utilize.
  - Availability for complete facility needs to be evaluated instead of individual system
- Lately published Assessment of PIP-II operational availability for PIP-II SRF facility, A.Saini, This model can be adapted and scaled for ILC.
Summary

• A lot of studies had been performed for ILC Linac and that can be adapted for new linear collider proposals.

• Some studies need to be updated
  – Realistic misalignments
  – Availability Analyses.
### TDR Parameter Lists

<table>
<thead>
<tr>
<th>Centre-of-mass energy $E_{CM}$ (GeV)</th>
<th>200</th>
<th>230</th>
<th>250</th>
<th>350</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Luminosity pulse repetition rate</strong></td>
<td>Hz</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Positron production mode</td>
<td>Hz</td>
<td>10 Hz</td>
<td>10 Hz</td>
<td>10 Hz</td>
<td>nom.</td>
</tr>
<tr>
<td>Estimated AC power $P_{AC}$ (MW)</td>
<td>114</td>
<td>119</td>
<td>122</td>
<td>121</td>
<td>163</td>
</tr>
<tr>
<td>Bunch population $N$ $\times 10^{10}$</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Number of bunches $n_b$</td>
<td>1312</td>
<td>1312</td>
<td>1312</td>
<td>1312</td>
<td>1312</td>
</tr>
<tr>
<td>Linac bunch interval $\Delta t_b$ ns</td>
<td>554</td>
<td>554</td>
<td>554</td>
<td>554</td>
<td>554</td>
</tr>
<tr>
<td>RMS bunch length $\sigma_z$ $\mu$m</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Normalized horizontal emittance at IP $\gamma_x$ $\mu$m</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Normalized vertical emittance at IP $\gamma_y$ nm</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Horizontal beta function at IP $\beta_x$ mm</td>
<td>16</td>
<td>14</td>
<td>13</td>
<td>16</td>
<td>11</td>
</tr>
<tr>
<td>Vertical beta function at IP $\beta_y$ mm</td>
<td>0.34</td>
<td>0.38</td>
<td>0.41</td>
<td>0.34</td>
<td>0.48</td>
</tr>
<tr>
<td>RMS horizontal beam size at IP $\sigma_x$ nm</td>
<td>904</td>
<td>789</td>
<td>729</td>
<td>684</td>
<td>474</td>
</tr>
<tr>
<td>RMS vertical beam size at IP $\sigma_y$ nm</td>
<td>7.8</td>
<td>7.7</td>
<td>7.7</td>
<td>5.9</td>
<td>5.9</td>
</tr>
<tr>
<td>Vertical disruption parameter $D_y$</td>
<td>24.3</td>
<td>24.5</td>
<td>24.5</td>
<td>24.3</td>
<td>24.6</td>
</tr>
<tr>
<td>Fractional RMS energy loss to beamstrahlung $\delta_{BS}$ %</td>
<td>0.65</td>
<td>0.83</td>
<td>0.97</td>
<td>1.9</td>
<td>4.5</td>
</tr>
<tr>
<td>Luminosity $L$ $\times 10^{34}$ cm$^{-2}$ s$^{-1}$</td>
<td>0.56</td>
<td>0.67</td>
<td>0.75</td>
<td>1.0</td>
<td>1.8</td>
</tr>
<tr>
<td>Fraction of $L$ in top 1% $E_{CM}$ $L_{0.01}$ %</td>
<td>91</td>
<td>89</td>
<td>87</td>
<td>77</td>
<td>58</td>
</tr>
<tr>
<td>Electron polarisation $P_-$ %</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Positron polarisation $P_+$ %</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Electron relative energy spread at IP $\Delta p/p$ %</td>
<td>0.20</td>
<td>0.19</td>
<td>0.19</td>
<td>0.16</td>
<td>0.13</td>
</tr>
<tr>
<td>Positron relative energy spread at IP $\Delta p/p$ %</td>
<td>0.19</td>
<td>0.17</td>
<td>0.15</td>
<td>0.10</td>
<td>0.07</td>
</tr>
</tbody>
</table>

\[
P_{Beam} = n_{Bunch} \cdot N_{Bunch} \cdot f_{rep} \cdot E \\
\approx 5 MW
\]
• Emittance growth
  – Does CLIC need earths curvature
  – iLC is truly global projects. Experts around the world came together to solve accelerator and beam physics challenges. Mitigation strategies developed for those issues are adaptable and scalable. I will review these work.
Fault Scenarios
Dispersion Functions along the Linac

- Maximum vertical dispersion in the linac is $\sim 1 \times 10^{-2}$ (m).
- Horizontal dispersion is zero in the linac.