The International Linear Collider

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University of Oregon
Introduction - the ILC

- **International community** plans initial ILC phase at 250 GeV.
- \( e^+e^- \) at 250 GeV addresses **compelling physics** questions:
  - EW symmetry breaking and Higgs physics,
  - Searches, more.
- ILC is **technically mature** with detailed, manageable cost estimate.
- Linear Colliders offer **natural evolution** to higher \( e^+e^- \) energy:
  - 350/380 GeV, 500 GeV, and higher.
- Upgradability well defined - **500 GeV ILC design** exists - TDR.
- **Political support** in Japan very strong with decision anticipated.
- ICFA & KEK planning **next framework**, beyond LCC/LCB.
Advantage of Higgs Studies at ILC

Very low backgrounds and simple reactions in $e^+e^-$. Environment allows for detectors of unprecedented accuracy.

Also, all decay modes are observed in $e^+e^-$, with small, calculable backgrounds.

Higher precision, model-independent measurements feasible. Sub-1% coupling measurements achievable.

Polarization enhances sensitivity.

Energy extendability (to 500-1000 GeV) accesses top Yukawa and triple-Higgs couplings
Higgs Boson Cross Section

\[ P(\ell^-, \ell^+) = (-0.8, 0.3), \ M_h = 125 \text{ GeV} \]

Based on Full ILC Detector Simulation (ILD)

Toy MC Data
Signal + Background
Signal
Background
\[ e^+e^- \rightarrow \mu^+\mu^- + X @ 250 \text{ GeV} \]

International Linear Collider (ILC)

Design from two decades of GDE-led dedicated R&D, with significant DOE/NSF support on detectors.

ILC TDR is 5-volumes, published 12 June 2013

Key Technologies

Nano-beam Technology

SRF Accelerating Technology

Physics Detectors

Damping Ring

e- Source
e+ Source
e+ Main Linac
e- Main Linac

~20km

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial stage</th>
<th>TDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.M. Energy (GeV)</td>
<td>250</td>
<td>500</td>
</tr>
<tr>
<td>Length (km)</td>
<td>20</td>
<td>31</td>
</tr>
<tr>
<td>Luminosity (x10^{34})</td>
<td>1.35</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>(2.7, 5.4)</td>
<td></td>
</tr>
<tr>
<td>Repetition (Hz)</td>
<td>5 (10)</td>
<td>5</td>
</tr>
<tr>
<td>Beam Pulse Period (ms)</td>
<td>0.73</td>
<td>0.73</td>
</tr>
<tr>
<td>Beam Current (mA in pulse)</td>
<td>5.8</td>
<td>5.8</td>
</tr>
<tr>
<td>Beam size (y) at FF (nm)</td>
<td>7.7</td>
<td>5.9</td>
</tr>
<tr>
<td>SRF Cavity Gr (MV/m), Q₀</td>
<td>31.5, 1x10^{10}</td>
<td>31.5, 1x10^{10}</td>
</tr>
<tr>
<td>Site Power (MW)</td>
<td>129</td>
<td>163</td>
</tr>
</tbody>
</table>

Polarized electrons (± 80%) and positrons (± 30%)

Based on S. Michizono, 8 Nov 2017

arXiv: 1711.00568
arXiv: 1903.01629

The International Linear Collider

J. Brau - Virtual Workshop - 22 April 2020
Linear and Circular Higgs Factory Parameter Comparison

Lumi & Power

Linear Collider provides power efficient lumi. for > 250 GeV
### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.M. Energy</td>
<td>250 GeV</td>
</tr>
<tr>
<td>Beam Rep. rate</td>
<td>5 Hz</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>0.73 ms</td>
</tr>
<tr>
<td>Av. field gradient</td>
<td>31.5(35) MV/m +/-20%</td>
</tr>
<tr>
<td>Q₀</td>
<td>1E10</td>
</tr>
</tbody>
</table>

**# 9-cell cavity**  
~8,000 (x 1.1)  

**# cryomodule**  
~900  

**# Klystron**  
~240  

High quality  

~8,000 x 1.1 (Yield = 90%)  
~9,000 cavities of mass-production  

Many accelerator projects, world-wide, applying and advancing SCRF technology. SCRF cavity production w/ N-infusion (Fermilab) pushing performance (see extras).
Effective Field Theory (EFT) (rather than coupling modifier $\kappa$ approach) delivers highly model-independent Higgs couplings.

Polarization Trades Off Against Increased Luminosity

- Increased sensitivity relative to unpolarized collisions.

LC - current, unimproved projections (S1*) validated by detailed simulation

see Tables XVIII and XIX of arXiv:1903.01629
Polarization Trades Off Against Increased Luminosity

- Increased sensitivity relative to unpolarized collisions.

For Higgs coupling measurements, polarization compensates for lower 250 GeV integrated luminosity (2 vs 5 ab⁻¹) by

1.) increased rates, and
2.) removing some correlations between EFT operators.

ALSO - ILC can provide a polarized Giga-Z program (6 billion Z"s) competitive with unpolarized Tera-Z when systematic errors are accounted; see arXiv:1908.11299

See Tables XVIII and XIX of arXiv:1903.01629
HL-LHC Comparison (model-dependent)

Assume:
1.) Higgs boson has no decay modes beyond those predicted by SM,
2.) Higgs boson WW & ZZ couplings modified only by rescaling.

- S1, current projection
- /model-dependent
- S2, improved
- /model-dependent (HL-LHC adopted)

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BSM Model Discrimination

- Studied nine (9) models that are unlikely to be discovered by HL-LHC.
- Masses beyond reach.

Improves (250+500)

- S1*, current projection / model-independent
- S2*, improved / model-independent

arXiv:1710.07621
The Broader Physics Program

The physics opportunities of the ILC emphasizes precise measurements of most Higgs boson couplings.

These are the centerpiece and FIRST PRIORITY.

But the ILC also provides:

- search for **exotic modes of Higgs boson decay**
- search for **dark matter particles and other invisible states**
- search for **heavy resonances** through 2-fermion processes
- precise study of **W boson interactions** in $e^+e^- \rightarrow W^+W^-$
- precise measurement of the **top quark mass**
- precise measurement of **top quark electroweak couplings**
- precise measurement of **top quark Yukawa coupling (tth)**
- measurement of the **triple Higgs boson coupling**
ILC Experimental Advantages

- Radiation damage is mostly not an issue (except very forward).
- Collisions dominated by electroweak processes.
- Trigger-less operation - record every interaction (< 6Gb/sec).
- Bunch train structure allows pulse power w/ gas cooling.

- Relatively low event rates.
- Elementary interactions at known $E_{cm}$ (e.g. $e^+e^- \rightarrow Z H$).
- Democratic Cross sections (e.g. $[e^+e^- \rightarrow ZH] \sim 1/2 [e^+e^- \rightarrow dd]$).
- Highly Polarized Electron Beam ($\sim 80\%$ - & positron pol. 30%).
- Tunable center-of-mass energy.
- Beam polarization helps control systematics.

- THESE FEATURES ENHANCE PRECISION MEASUREMENTS
Physics Drives Detector Requirements

<table>
<thead>
<tr>
<th>Physics Process</th>
<th>Measured Quantity</th>
<th>Critical System</th>
<th>Critical Detector Characteristic</th>
<th>Required Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow b\bar{b}, c\bar{c}, gg, \tau\tau$</td>
<td>Higgs branching fractions (b) quark charge asymmetry</td>
<td>Vertex Detector</td>
<td>Impact parameter (\Rightarrow) Flavor tag</td>
<td>(\delta_b \sim 5\mu m \oplus 10\mu m / (p \sin^{3/2} \theta))</td>
</tr>
<tr>
<td>$ZH \rightarrow \ell^+ \ell^- X$</td>
<td>Higgs Recoil Mass (\mu^+ \mu^- \gamma) Lumin Weighted $E_{cm}$ BR (H $\rightarrow \mu\mu$) (\rightarrow \mu^+ \mu^- X)</td>
<td>Tracker</td>
<td>Charge particle momentum resolution, (\sigma(p_t)/p_t^2) (\Rightarrow) Recoil mass</td>
<td>(\sigma(p_t)/p_t^2 \sim few \times 10^{-5} \text{GeV}^{-1})</td>
</tr>
<tr>
<td>$ZHH$</td>
<td>Triple Higgs Coupling Higgs Mass (\nu\bar{\nu}W^+W^-) BR (H $\rightarrow \mu\mu$) (\sigma(e^+e^- \rightarrow \nu\nu W^+W^-))</td>
<td>Tracker &amp; Calorimeter</td>
<td>Jet Energy Resolution, (\sigma_E/E) (\Rightarrow) Di-jet Mass Res.</td>
<td>(~3%) for $E_{\text{jet}} &gt; 100 \text{ GeV}$ (30% / \sqrt{E_{\text{jet}}}) for $E_{\text{jet}} &lt; 100 \text{ GeV}$</td>
</tr>
<tr>
<td>SUSY, eg. (\tilde{\mu}) decay</td>
<td>(\tilde{\mu}) mass</td>
<td>Tracker, Calorimeter</td>
<td>Momentum resolution, Hermiticity (\Rightarrow) Event Reconstruction</td>
<td>Maximal solid angle coverage</td>
</tr>
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</table>
Integrated Detectors

- Two Validated detector concepts.
- Complementary: tracking technology, magnetic field, calorimetry, etc.
- Expect new ideas & concepts to be considered as project matures.
- Collaborators welcome.

<table>
<thead>
<tr>
<th>Design</th>
<th>High efficiency</th>
</tr>
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<tbody>
<tr>
<td>Goals:</td>
<td>High resolution</td>
</tr>
<tr>
<td></td>
<td>Low fake rate</td>
</tr>
<tr>
<td></td>
<td>Control of systematics</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>SiD</th>
<th>ILD</th>
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<tbody>
<tr>
<td>Silicon</td>
<td>Tracking</td>
</tr>
<tr>
<td>TPC w/ silicon</td>
<td></td>
</tr>
<tr>
<td>6.0 m</td>
<td>Outer Radius</td>
</tr>
<tr>
<td>7.8 m</td>
<td></td>
</tr>
<tr>
<td>5 Tesla</td>
<td>B Field</td>
</tr>
<tr>
<td>3.5 Tesla</td>
<td></td>
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</table>

SiD

ILD
Unprecedented subDetectors (examples)

Silicon tracking w/ gas cooling → Low material

SiD Tracker Design
❖ Linkage between readout/mechanics/powering/cooling studies.
❖ Maintain low mass construction.
❖ Tracking material from SiD design:

Silicon-tungsten ECAL - very high granularity

SiD ECAL Design
❖ 6 inch wafers, 1024 13 mm² pixels
❖ KPiX readout/cable bump-bonded directly
❖ 1 mm readout gaps -> 13 mm eff. Moliere radius
❖ Tungsten thermal bridge
Detector Requirements Achieved in Designs

- Clean events with low backgrounds enable unprecedented detector performance motivated by physics goals.
  - High granularity
  - Dense integration
  - Super light materials
  - Low power/pulse power
  - Air cooling
- Physics simulations are based on realistic detector models.
- Renewed US Detector R&D support needed to re-establish US roles.
Annual International Workshops on Future Linear Colliders

2019 LINEAR COLLIDER WORKSHOP
❖ October 28-Nov 1, 2019 - Sendai, Japan, LCWS2019

❖ 2018 - Arlington, Texas
❖ 2017 - Strasbourg, France

October, 2019 - Sendai
Reaffirmed Japanese government’s interest in hosting the ILC.

"US-Japan relation is stronger than ever, and the political and administrative aspects are both working towards the realization of the ILC.”
Melinda Pavek, Director of Science, Innovation and Development, US Embassy, Tokyo

“the U.S. Department of State is ready to assist our partner agencies in developing the next major particle physics facility in Japan—the International Linear Collider.”
Two leading Japanese figures in the decision process came to SLAC to address ICFA.

- **H. Masuko**, Deputy-Director General, MEXT.
- **T. Kawamura**, Chairperson of the Federation of Diet Members for the ILC.

Both gave encouraging statements.

- **Chris Fall**, Director of US DOE Office of Science, also appear in person and gave positive ILC statement.

In response, ICFA released a statement (next slide).

ICFA Statement on the ILC Project
February 22, 2020

ICFA was encouraged by the reports from Mr. H. Masuko, Deputy-Director General, MEXT Research Promotion Bureau and Hon. T. Kawamura, Chairperson of the Federation of Diet Members for the ILC, at the ICFA meeting held at the SLAC National Accelerator Laboratory, Stanford, USA, on the 20th February 2020.

In view of progress towards realisation of the ILC in Japan, ICFA encourages the interested members of the high energy physics community, laboratories, and nations, to support and participate in these preparations aimed at the successful establishment of the ILC.


- ICFA anticipates that these development activities could be completed in approximately one year, at which point it would be possible to launch the preparatory phase for the ILC, provided Japan expresses intent to do so together with international partners.

- In view of progress towards realisation of the ILC in Japan, ICFA encourages the interested members of the high energy physics community, laboratories, and nations, to support and participate in these preparations aimed at the successful establishment of the ILC.

Menlo Park, CA, USA
Development Team

- Linear Collider Collaboration, led by Lyn Evans, mandate ends June, 2020.
- ICFA, assisted by LCB, led by Tatsuya Nakada, planning a transition phase, led by an international development team, hosted by KEK. (Transition will last approx. 1-1.5 years.)
- International development team plans pre-Lab preparatory phase including technical, organizational and governance issues and the activities and resources required in the pre-Lab preparatory phase.
- Following about one year planning, if Japan has expressed intent with international partners, pre-Lab preparatory phase will be launched.

Conclusion

❖ ILC is technically sound, ready for construction start.
❖ Staged ILC offers excellent science from first stage (250 GeV)
❖ TeV-scale BSM physics impacts Higgs boson couplings at the percent level. (polarization and model-independence critical)
❖ Higher energy upgrades will extend physics program.
❖ All LHC scenarios leave a compelling ILC discovery potential.
❖ ICFA recently heard encouraging reports on status from leading Japanese political and governmental figures.
❖ ICFA preparing plan for transition from LCC/LCB.
❖ US DOE and State encourages Japanese.
❖ High-level “signal” within Japanese government soon.
❖ Join us as we transition to ILC Lab.
Acknowledgement

- Support provided by US Department of Energy.
ILC References

- International Linear Collider Technical Design Report
  arXiv:1306.6327 – Volume 1: Executive Summary

- Physics Case for the 250 GeV Stage of the International Linear Collider
  arXiv:1710.07621

- The International Linear Collider Machine Staging Report 2017
  arXiv:1711.00568

- The role of positron polarization for the initial 250 GeV stage of the International Linear Collider
  arXiv:1801.02840

- The International Linear Collider: A Global Project
  arXiv:1903.01629

- Tests of the Standard Model at the International Linear Collider
  arXiv:1908.11299v2