ILC Accelerator at Z, H and tt

Kaoru Yokoya, KEK
2017.1.23 IAS at HKUST
• ILC-TDR (Technical Design Report) describes the design optimized for $E_{\text{CM}} = 500\text{GeV}$

• Parameter sets for 200, 230, 250, 350 and 1000GeV are also given but not in detail
  • Next slide. The values of luminosity corrected after TDR

• There is no official parameter set for 92 GeV

• Basically, linear colliders are not good at low energies
<table>
<thead>
<tr>
<th>Parameter</th>
<th>E&lt;sub&gt;cm&lt;/sub&gt;</th>
<th>L Upgrade</th>
<th>Ecm Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre-of-mass energy</td>
<td>E&lt;sub&gt;cm&lt;/sub&gt;</td>
<td>GeV</td>
<td>200</td>
</tr>
<tr>
<td>Beam energy</td>
<td>E&lt;sub&gt;beam&lt;/sub&gt;</td>
<td>GeV</td>
<td>100</td>
</tr>
<tr>
<td>Collision rate</td>
<td>f&lt;sub&gt;rep&lt;/sub&gt;</td>
<td>Hz</td>
<td>5</td>
</tr>
<tr>
<td>Electron linac rate</td>
<td>f&lt;sub&gt;linac&lt;/sub&gt;</td>
<td>Hz</td>
<td>10</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>n&lt;sub&gt;b&lt;/sub&gt;</td>
<td></td>
<td>1312</td>
</tr>
<tr>
<td>Bunch population</td>
<td>N</td>
<td>x10&lt;sup&gt;10&lt;/sup&gt;</td>
<td>2</td>
</tr>
<tr>
<td>Bunch separation</td>
<td>Δ&lt;sub&gt;tb&lt;/sub&gt;</td>
<td>ns</td>
<td>553.8</td>
</tr>
<tr>
<td>Bunch separation x f&lt;sub&gt;RF&lt;/sub&gt;</td>
<td>Δ&lt;sub&gt;tb&lt;/sub&gt; f&lt;sub&gt;RF&lt;/sub&gt;</td>
<td></td>
<td>720</td>
</tr>
<tr>
<td>Pulse current</td>
<td>I&lt;sub&gt;beam&lt;/sub&gt;</td>
<td>mA</td>
<td>5.79</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>σ&lt;sub&gt;z&lt;/sub&gt;</td>
<td>mm</td>
<td>0.3</td>
</tr>
<tr>
<td>Electron RMS energy spread</td>
<td>Δp/p</td>
<td>%</td>
<td>0.206</td>
</tr>
<tr>
<td>Positron RMS energy spread</td>
<td>Δp/p</td>
<td>%</td>
<td>0.187</td>
</tr>
<tr>
<td>Electron polarisation</td>
<td>P&lt;sup&gt;-&lt;/sup&gt;</td>
<td>%</td>
<td>80</td>
</tr>
<tr>
<td>Positron polarisation</td>
<td>P&lt;sup&gt;+&lt;/sup&gt;</td>
<td>%</td>
<td>31</td>
</tr>
<tr>
<td>Horizontal emittance at IP</td>
<td>γε&lt;sub&gt;x&lt;/sub&gt;</td>
<td>μm</td>
<td>10</td>
</tr>
<tr>
<td>Vertical emittance at IP</td>
<td>γε&lt;sub&gt;y&lt;/sub&gt;</td>
<td>nm</td>
<td>35</td>
</tr>
<tr>
<td>IP horizontal beta function</td>
<td>β&lt;sub&gt;x&lt;/sub&gt;*</td>
<td>mm</td>
<td>16</td>
</tr>
<tr>
<td>IP vertical beta function</td>
<td>β&lt;sub&gt;y&lt;/sub&gt;*</td>
<td>mm</td>
<td>0.34</td>
</tr>
<tr>
<td>IP RMS horizontal beam size</td>
<td>σ&lt;sub&gt;x&lt;/sub&gt;*</td>
<td>nm</td>
<td>904</td>
</tr>
<tr>
<td>IP RMS vertical beam size</td>
<td>σ&lt;sub&gt;y&lt;/sub&gt;*</td>
<td>nm</td>
<td>7.80</td>
</tr>
<tr>
<td>Horizontal disruption parameter</td>
<td>D&lt;sub&gt;x&lt;/sub&gt;</td>
<td></td>
<td>0.210</td>
</tr>
<tr>
<td>Vertical disruption parameter</td>
<td>D&lt;sub&gt;y&lt;/sub&gt;</td>
<td></td>
<td>24.3</td>
</tr>
<tr>
<td>Geometric luminosity</td>
<td>L&lt;sub&gt;geom&lt;/sub&gt;</td>
<td>10&lt;sup&gt;34&lt;/sup&gt; /cm&lt;sup&gt;2&lt;/sup&gt;s</td>
<td>0.296</td>
</tr>
<tr>
<td>Average beamstrahlung parameter</td>
<td>Y&lt;sub&gt;av&lt;/sub&gt;</td>
<td></td>
<td>0.013</td>
</tr>
<tr>
<td>Maximum beamstrahlung parameter</td>
<td>Y&lt;sub&gt;max&lt;/sub&gt;</td>
<td></td>
<td>0.031</td>
</tr>
<tr>
<td>Average number of photons / particle</td>
<td>n&lt;sub&gt;γ&lt;/sub&gt;</td>
<td></td>
<td>0.95</td>
</tr>
<tr>
<td>Luminosity</td>
<td>L</td>
<td>10&lt;sup&gt;34&lt;/sup&gt; /cm&lt;sup&gt;2&lt;/sup&gt;s</td>
<td>0.59</td>
</tr>
<tr>
<td>Luminosity enhancement factor</td>
<td>H&lt;sub&gt;D&lt;/sub&gt;</td>
<td></td>
<td>1.99</td>
</tr>
<tr>
<td>Fraction of luminosity in top 1%</td>
<td>L&lt;sub&gt;0.01&lt;/sub&gt;/L</td>
<td></td>
<td>0.913</td>
</tr>
<tr>
<td>Average energy loss</td>
<td>δ&lt;sub&gt;EBS&lt;/sub&gt;</td>
<td>%</td>
<td>0.65</td>
</tr>
<tr>
<td>Number of pairs per bunch crossing</td>
<td>N&lt;sub&gt;pairs&lt;/sub&gt; x10&lt;sup&gt;3&lt;/sup&gt;</td>
<td></td>
<td>45</td>
</tr>
<tr>
<td>Total pair energy per bunch crossing</td>
<td>E&lt;sub&gt;pairs&lt;/sub&gt;</td>
<td>TeV</td>
<td>25</td>
</tr>
</tbody>
</table>
Proposed Operation Scenario (ICHEP2016)

• 500GeV machine assumed
• Start with 500GeV, then, →350, → 250GeV
• Luminosity upgrade: 1312 bunches → 2625 bunches
10Hz Operation at 250GeV

• Beaseline design in TDR: 5Hz
• 10Hz operation is possible at 250GeV
  • Assume 500GeV machine
  • 10Hz possible only at 250GeV
    • < 250GeV: poor positron yield
    • > 250GeV: power excess
• Proposed after TDR (~summer 2013)
• Damping rings support 10Hz operation (already in TDR)
  • Strong wigglers, doubled RF system
• Linac RF system accepts 10Hz
  • Klystron ready (XFEL)
• Total power nearly the same as 5Hz at 500GeV
  • Gradient is only half of 500GeV
• The only uncertainty is positron target
• Proposed scenario (ICHEP2016) assumes 10Hz collision
Luminosity Limit at 250GeV

• Simple scaling: \( L \propto E_{CM} \)

\[
\mathcal{L} = f_{rep} \frac{n_b N^2}{4\pi \sigma_x^* \sigma_y^*} \times H_D
\]

• Geometric emittance proportional to \( 1/\gamma \)
• However, beam angle spread gives a strong constraint at < 250GeV
  • Causes background from synchrotron radiation of large amplitude particles in the final quads
  • Deep collimation necessary
• This effect is already visible at 250GeV
• TDR gives \( 0.82 \times 10^{34} @250\text{GeV} \)
  • \( 1.79 \times 10^{34} @500\text{GeV} \)
Baseline Positron Production Scheme

- Undulator method
  - Undulator
    - Placed at the end of the electron linac
    - Helical, superconducting
    - Length ~150m (~230m when highly polarized positron is needed)
    - $K=0.92$, $\lambda=1.15\text{cm}$, ($B=0.86\text{T}$ on the axis)
    - beam aperture 5.85mm (diameter)
- Target: rotating titanium alloy
- Flux Concentrator for positron capture
- Normal-conducting acceleration up to 400MeV
- Polarization ~30% (~60% with photon collimator and longer undulator)
e-Driven Positron Source

- Conventional method (electron-driven source) is also being considered
- Hit ~5 GeV electrons on a target, and collect the generated positrons
- All normal-conducting
- No polarized positron
- 10Hz collision impossible (up to ~6.1Hz)
Operation Below 250GeV

- The positron production scheme using undulator causes a problem at low energies.
- For $E_{CM} > 250$GeV, use electron for collision:
  - i.e., $E_e = E_{CM}/2$
- Positron production yield depends on $E_e$ →
- Poor production rate below $E_e = 125$GeV
- Study being done for shorter pitch, e.g., using Nb$_3$Sn, but not ready.
  - Z-pole is anyway impossible

Yield and Polarization of 231m RDR undulator without photon collimator
OMD is QWT

Yield vs. Drive beam energy (GeV)

Polarization
5+5Hz Operation

- For $E_{\text{CM}} < 250\text{GeV}$,
  - Operate electron linac at 10Hz
    - 5Hz for colliding beam ($E_e = E_{\text{CM}}/2$)
    - 5Hz for positron production ($E_e = 150$ or 125GeV)
  - Already in TDR
  - This is the reason that DRs are ready for 10Hz operation

- Spent electron after positron production must be dumped

- Operation at Z-pole is possible in simple principle but..............
5+5Hz Operation Hardware

- Hardware requirements
  - 5Hz switching of accelerating gradient
    - Hardware not seriously studied, but should be OK
    - To turn-off some of the cryomodules is presumably impossible (5Hz detuning for empty cavities needed)
    - Lower gradient operation may cause some beam dynamics issues (discuss later)
  - Damping in 100ms in DRs
    - Strong wigglers already in TDR
  - 5Hz pulsed magnets needed before and after the undulator
  - Dump line and dump (up to 6.3MW) for the spent electron after producing positron
Luminosity vs. $E_{CM}$

Figure 1: ILC luminosity parameters versus centre-of-mass energy. Data points are the published numbers [1], with the exception of the 90 GeV and 160 GeV analytical points. The $\gamma^{3/2}$ scaling (from the 250 GeV luminosity) is also shown.
Luminosity at Z-pole

- \[ L = f_{\text{rep}} \times N_{\text{bunch}} \times N^2 / 4\pi \sigma_x \sigma_y \]
- Naive scaling: \( \sigma_x \sigma_y \) is proportional to \( \sqrt{\varepsilon_x \varepsilon_y} \) \( \sim 1/E_{\text{CM}} \) \( \rightarrow \) \( L \sim E_{\text{CM}} \)
- But the larger beam divergence near IP due to the larger emittance at low energies would cause background
- A more conservative scaling is \( L \sim E_{\text{CM}}^{3/2} \) or \( E_{\text{CM}}^2 \)
  - Horizontal angle is already at the limit at \( E_{\text{CM}} = 250 \text{GeV} \)
  - \( L \sim E_{\text{CM}}^{3/2} \) if horizontal plane only
  - \( L \sim E_{\text{CM}}^2 \) if both planes
- This would result in \( L=1.5 \times 10^{33} \) or \( 1 \times 10^{33} \) at Z-pole
- Further reduction of luminosity may be expected because of the beam dynamics (emittance increase) of low gradient operation
  - \( \rightarrow \) next pages
- Can still be used for detector calibration
Beam Dynamics: Positron production beam

- 2 different energy beams in electron main linac
- Orbit is tuned for the colliding beam ($E_{CM}/2$)
- The positron production beam (125GeV or 150GeV) will shift vertically due to earth-following curvature

- The orbit difference is $O(1\text{mm})$ for $E_{CM}/2=100\text{GeV}$,
- but $>10\text{mm}$ for $E_{CM}/2=45$
- Orbit difference itself can be corrected by pulsed magnets at main linac exit
Beam Dynamics : Colliding Beam (1)

• Main linac
  • Low gradient operation necessary
    • Note: for the case e-driven source, emittance increase problem is not serious because “full gradient plus empty cavity” is possible
  • Emittance increase due to energy spread + misalignment: \( \Delta \varepsilon \propto \left( \frac{\sigma_E}{E} \right)^2 \propto \left( \frac{E_0}{E} \right)^2 \)
    • \( \sigma_E \) (fixed)
    • \( (250/45)^2 \sim 30 \) or, may be, \( (125/45)^2 \sim 8 \)
  • Emittance increase due to wakefield also proportional to \( 1/E^2 \)
  • Emittance budget in TDR to decide the alignment tolerance is \( \Delta \varepsilon_y / \varepsilon_y = 10\text{nm} / 20\text{nm} = 0.5 \)

• Undulator
  • Emittance increase due to resistive wakefield proportional to \( 1/E^2 \)
  • Radiated photon angle \( 1/\gamma = 10^{-5} \): intercepted by the downstream undulators
    Mask radius 2.3mm / length up to 200m \( \sim 10^{-5} \)
  • If the colliding beam cannot go through the undulator, a bypass line must be constructed
Emittance growth vs. final energy

Average of 40 random seeds. Error bar: standard deviation.

- $\varepsilon_0 = 20\text{nm}$
- Linac length for 250GeV
- Uniform gradient over whole linac
- Random alignment errors
- DFS correction

Final Beam Energy (GeV)

20161201 K.Kubo, preliminary
• BDS
  • Final quads
    • QD0 is split into 2 parts (1m+1m) in TDR
    • Upstream half is turned off for $E_{CM} = 250\text{GeV}$ operation (to make effective $L^*$ small)
    • However, further shorter magnet (0.5m) would not gain much
    • Anyways, replacement of QD0 is meaningless for calibration purpose
  • Emittance increase in BDS
  • Collimation depth
    • To avoid background, the collimators must cut the beam closer to the beam center
    • Must use the emittance increased in the main linac
• For all these beam dynamics issues, serious studies are needed
Giga-Z

• 5+5Hz scenario is not sufficient for Giga-Z
• N.Walker suggests a scheme below for Giga-Z
  • Split electron linac into 2 parts
  • Prepare an additional electron gun and a long transport line of colliding electron beam
• This would require a big change in the design

Figure 2: "Giga Z" configuration for polarised positron production.
One of the detector teams (ILD) requires the luminosity for detector calibration \(2 \times 10^{32} \text{ 1/cm}^2\text{/s} \) at Z-pole.

This is presumably feasible by 5+5Hz operation, though serious studies are needed.

Once operation below 250GeV turns out to be necessary, the requirement of Z-pole calibration would not cause additional cost.

- If any operation below 250GeV (including calibration) is not needed, the cost saving is significant.

In any case the luminosity required for Giga-Z seems to be too far, unless strongly desired.
Staging

• Strong demand for cost reduction

• Improvement of linac technology is under study
  • Higher gradient: e.g., 31.5MV/m $\rightarrow$ 35MV/m
  • Higher Q values: e.g., $1 \times 10^{10} \rightarrow 2 \times 10^{10}$
  • Nitrogen infusion being developed at FNAL
  • But the cost reduction is at most 10-15%

• Recent trend is to consider staging to reduce the first stage cost

• Starting with $E_{CM} = 250\text{GeV}$ is a reasonable choice

• The choice whether 500GeV tunnel or just 250GeV tunnel is still under debate
Possible Staging Scenarios of ILC

TDR 500GeV CM

Option A: 350GeV CM

Option B: 250GeV CM, 350GeV tunnel

Option C: 250GeV CM

Option D: 250GeV CM, 500GeV tunnel

Option E: 250GeV CM, 500GeV tunnel

Option F: 250GeV CM with spacing, 500GeV tunnel
Physics Demand: Higher L @250GeV

• 10Hz collision @250GeV is possible only with option F
  • Requires full RF system of 500GeV
  • But this would be somewhat expensive

• With other options, the only way of raising the luminosity is to focus the beam more (in particular, in horizontal plane)
  • i.e., more beamstrahlung (1% $\rightarrow$ 4% is acceptable from physics)
  • $L \propto \frac{1}{\sigma_x, \delta_{bs}}$ to $\frac{1}{\sigma_x^2}$

\[
L \approx C \frac{P_B}{E} \sqrt{\frac{\delta_{BS}}{\epsilon_{y,n}}} \min \left( 1, \sqrt{\frac{\sigma_z}{\beta_y^*}} \right)
\]

• However, the horizontal angle effect is the limiting factor
• What about re-designing the damping ring for lower horizontal emittance
  • Present design is very conservative in this respect
Summary

• Baseline luminosity at $E_{CM} = 250\text{GeV}$ is $\sim 0.82 \times 10^{34}$
• Luminosity can be doubled by doubling the number of bunches ($1312 \rightarrow 2625$)
• Another factor of 2 is possible by 10Hz collision, if 500GeV machine is built
• Recently staging (starting at 250GeV) is demanded to reduce the first stage cost
  • 10Hz collision is presumably difficult
  • The only way to increase the luminosity at 250GeV is to lower the horizontal emittance
• Luminosity at Z-pole is somewhat low, though sufficient for detector calibration
• Giga-Z is not realistic unless strongly desired