Lepton & Gamma Colliders for the Energy Frontier

Mark Palmer
Frontier Capabilities:
Energy Frontier Lepton & Gamma Colliders Sub-Group

CSS2013, June 28-August 6: “Snowmass on the Mississippi”
INTRODUCTION

The Working Group and Inputs

The Working Group Assessments

Comments on Making Comparisons
Frontier Capabilities: Lepton Colliders

• Accelerator Capabilities Convener: Bill Barletta (MIT)

• Lepton Colliders Working Group:
  • Sub-conveners: Marco Battaglia (UCSC), Markus Klute (MIT), Kaoru Yokoya (KEK), & myself
  • EF Liaison: Tor Raubenheimer (SLAC)
  • Sub-Group Meeting at MIT: https://indico.cern.ch/conferenceDisplay.py?ovw=True&confId=233944

• Submissions covered a broad range of capabilities and possibilities ⇒ many contributors to what follows
Working Group Assessment

• The goal of the working group has been to:
  – Summarize the capabilities that can support the physics needs of Energy Frontier
  – Evaluate the major technical challenges and cost drivers
  – Identify the R&D path required to develop the necessary capabilities

• It should be noted that:
  – All of the options have some technical challenges
  – None of the options under consideration is cheap
  – But, we do have real options with contrasting strengths and weaknesses (as well as varying states of readiness)

⇒ which makes the process of charting an optimal route forward challenging when we are discussing timescales of decades
Comment on Concept Maturity

• It should also be noted that the concepts described here span a broad range of maturity
  – R&D concepts requiring significant validation
  – Full technical designs where performance has been explicitly sacrificed in order to achieve something that can be built
    • And to fit within a specific budget profile
  – Design extrapolations
    • Based on well-understood individual technologies in many cases
    • However, not yet validated in full detail

• Thus capabilities comparisons are non-trivial at this level
  – Attention should be paid to “strategic” (ie, physics) benefits
  – Audience should ask pointed questions about how realistic any individual plan is
e^+e^- Circular Colliders: >100 GeV Scale
Linear Colliders:
  • e^+e^- Colliders with E < 1 TeV & E > 1 TeV
  • \(\gamma-\gamma\) Colliders
\(\mu^+\mu^-\) Colliders: Up to 10 TeV
**Comments**
- LEP2 nearly reached the Higgs
- Rings are robust and well-understood technology

**Technical Issues**
- Synchrotron Radiation
- RF Efficiency
- Beam Lifetime (~$10^3$ sec) and Top-Up Injection
- Collective Effects
- Energy Bandwidth

**Trends in the Discussion**
- Re-use of the LEP tunnel (conflict w/LHC) as well as various site-filler options initially discussed
- Recent focus: 80-100km ring leading to a 100 TeV scale hadron collider (VHE-LHC/VLHC)
- Takes a longer term view
- Limits SR issues
The TLEP Concept

350 GeV C.M. e⁺e⁻ ⇒ 100 TeV pp

J. Osborne, C. Waaijer
Electron-Positron Storage Rings: Parameters for Selected Options

<table>
<thead>
<tr>
<th></th>
<th>LEP2</th>
<th>TLEP* – HZ</th>
<th>TLEP* - t</th>
<th>FNAL** - HZ</th>
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<tbody>
<tr>
<td>Beam Energy [GeV]</td>
<td>104.5</td>
<td>120</td>
<td>175</td>
<td>120</td>
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<td>Circumference [km]</td>
<td>26.7</td>
<td>80</td>
<td>80</td>
<td>100</td>
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<td>Beam current [mA]</td>
<td>4</td>
<td>24.3</td>
<td>5.4</td>
<td>12.9</td>
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<td>Number of bunches</td>
<td>4</td>
<td>80</td>
<td>12</td>
<td>34</td>
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<tr>
<td>Bunch population ([10^{12}])</td>
<td>0.575</td>
<td>40.8</td>
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<td>0.79</td>
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<td>Horizontal emittance [nm]</td>
<td>48</td>
<td>9.4</td>
<td>10</td>
<td>16</td>
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<tr>
<td>Vertical emittance [nm]</td>
<td>0.25</td>
<td>0.02</td>
<td>0.01</td>
<td>0.08</td>
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<td>(\beta_x^*) [mm]</td>
<td>1500</td>
<td>500</td>
<td>1000</td>
<td>200</td>
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<tr>
<td>(\beta_y^*) [mm]</td>
<td>50</td>
<td>1</td>
<td>1</td>
<td>2</td>
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<tr>
<td>Hourglass factor</td>
<td>0.98</td>
<td>0.75</td>
<td>0.65</td>
<td>0.81</td>
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<td>SR power/beam [MW]</td>
<td>11</td>
<td>50</td>
<td>50</td>
<td>20</td>
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<tr>
<td>Bunch length [mm]</td>
<td>16</td>
<td>1.7</td>
<td>2.5</td>
<td>3.2</td>
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<tr>
<td>Momentum acceptance [%]</td>
<td>1.25</td>
<td>2.5</td>
<td>2.5</td>
<td>3.0</td>
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<tr>
<td>Beam-beam parameter / IP</td>
<td>0.07</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Luminosity / IP ([10^{34} \text{ cm}^{-2}\text{s}^{-1}])</td>
<td>0.0125</td>
<td>4.8</td>
<td>1.3</td>
<td>1.8</td>
</tr>
</tbody>
</table>

* Assumes 4 IPs
** Assumes 1 or 2 IPs
e^+e^- Circular Colliders

Status
- TLEP Design Study has been launched
- Not aware of any other significant effort underway

R&D
- Focus on detailed technical assessments
- Challenges, but no obvious showstoppers

Time
- TLEP: Conceptual Design Report by 2015
- TLEP: Technical Design Report by 2018
- TLEP: Aiming for construction readiness in 2020’s

Technical Statement
Linear Colliders

- Luminosity

\[ L = \frac{N^2 f_{\text{coll}}}{4\pi\sigma_x \sigma_y} \mathcal{H}_D \]

\[ L = \frac{P_b}{E_b} \left( \frac{N}{4\pi\sigma_x \sigma_y} \right) \mathcal{H}_D \]

- The strong fields at the interaction point result in
  - A luminosity enhancement characterized by the disruption parameter \( \mathcal{H}_D \)
  - Beamstrahlung emission gives rise to energy spread and backgrounds at the interaction point
Linear Collider Options

• A range of options have been explored
  – ILC: Based on SRF technology
    Most mature concept for $E_{CM} < 1$ TeV
  – CLIC: Based on drive-beam and NCRF technology
    RF Gradients: 100 MV/m
    Could be applied for $E_{CM} < 1$ TeV, but designs up to 3 TeV are documented

Yield '10 ~ '12:
> 90% @ 25 MV/m
~ 80% @ 28 MV/m
~ 70% @ 35 MV/m
Linear Collider Options

- Wakefield Accelerators:
  - Potential for very high energies
  - Possibly could be used for LC afterburner
  - Significant R&D remains

- $\gamma - \gamma$:
  - High power laser beams
  - Compton backscattered from $e^-$ or $e^+$ beams
  - $\gamma\gamma \rightarrow H$ cross section $\sim 200\text{fb}$
  - Concept could be applied at an ILC or CLIC
ILC in a Nutshell

Damping Rings

Polarised electron source

Ring to Main Linac (RTML) (inc. bunch compressors)

Polarised positron source

E- Main Linac

E+ Main Linac

Beam Delivery System (BDS) & physics detectors

Beam dump

Not to scale

Total site length (500 GeV CM) | 30.5 km
---|---
SCRF Main Linacs | 22.2 km
RTML (bunch compressors) | 2.8 km
Positron source | 1.1 km
BDS / IR | 4.5 km
Damping Rings (circumference) | 3.2 km

M. Ross
<table>
<thead>
<tr>
<th></th>
<th>1 TeV</th>
<th>1 TeV Baseline</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>150%</td>
<td>166%</td>
<td></td>
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<tr>
<td></td>
<td>263</td>
<td>298</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>14.6</td>
<td>27.3</td>
<td></td>
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<tr>
<td>Baseline</td>
<td>100%</td>
<td>106%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>163</td>
<td>204</td>
<td>500</td>
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<tr>
<td></td>
<td>10.5</td>
<td>21.0</td>
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<tr>
<td>LHF</td>
<td>69%</td>
<td>74%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>129</td>
<td>161</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>9.4</td>
<td>11.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1312</td>
<td>2625 / (2450 4Hz)</td>
<td>2625 10 Hz</td>
</tr>
<tr>
<td>Number of bunches and repetition rate -&gt;</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A factor of 2.5 in $L/P_{\text{wall}}$

### Luminosity vs Energy

![Luminosity vs Energy graph](image)

### Legend

<table>
<thead>
<tr>
<th></th>
<th>Title</th>
</tr>
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<tbody>
<tr>
<td>Rel Cost</td>
<td>$L (e34)$</td>
</tr>
<tr>
<td>P_AC (MW)</td>
<td>P_2 beam</td>
</tr>
</tbody>
</table>

M. Ross
1.3 GHz Nb 9-cell Cavities | 16,024
Cryomodules | 1,855
SC quadrupole pkg | 673
10 MW MB Klystrons & modulators | 436 *

* site dependent

Approximately 20 years of R&D worldwide → Mature technology

M. Ross

Graphics by Rey. Hori

10 MW MB Klystron
Building ILC in Japanese Mountains:

- Reduced surface presence.
- Horizontal access
- Most infrastructure underground.

"Mountainous" Topography site-dependent design

"Kamaboko" tunnel

Access Hall

M. Ross
Candidate site (1 of 2) in northeastern Japan

Tohoku ‘Mountain Region’

(Photographed 100 km north of Sendai.)

The ILC alignment would be 50 to 400 meters below these hills.
## ILC Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
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<tbody>
<tr>
<td><strong>Centre-of-mass energy</strong> E&lt;sub&gt;cm&lt;/sub&gt; GeV</td>
<td>250</td>
<td>350</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td><strong>Beam energy</strong> E&lt;sub&gt;beam&lt;/sub&gt; GeV</td>
<td>125</td>
<td>175</td>
<td>250</td>
<td>500</td>
</tr>
<tr>
<td><strong>Estimated AC power</strong> P&lt;sub&gt;AC&lt;/sub&gt; MW</td>
<td>128</td>
<td>142</td>
<td>162</td>
<td>300</td>
</tr>
<tr>
<td><strong>Collision rate</strong> f&lt;sub&gt;rep&lt;/sub&gt; Hz</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td><strong>Electron linac rate</strong> f&lt;sub&gt;linac&lt;/sub&gt; Hz</td>
<td>10</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td><strong>Number of bunches</strong> n&lt;sub&gt;b&lt;/sub&gt;</td>
<td>1312</td>
<td>1312</td>
<td>1312</td>
<td>2450</td>
</tr>
<tr>
<td><strong>Bunch separation</strong> Dt&lt;sub&gt;b&lt;/sub&gt; ns</td>
<td>554</td>
<td>554</td>
<td>554</td>
<td>366</td>
</tr>
<tr>
<td><strong>Pulse current</strong> I&lt;sub&gt;beam&lt;/sub&gt; mA</td>
<td>5.8</td>
<td>5.8</td>
<td>5.79</td>
<td>7.6</td>
</tr>
<tr>
<td><strong>RMS bunch length</strong> σ&lt;sub&gt;z&lt;/sub&gt; mm</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.250</td>
</tr>
<tr>
<td><strong>Electron polarisation</strong> P&lt;sub&gt;-&lt;/sub&gt; %</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td><strong>Positron polarisation</strong> P&lt;sub&gt;+&lt;/sub&gt; %</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td><strong>Luminosity (inc. waist shift)</strong> L x10&lt;sup&gt;34&lt;/sup&gt; cm&lt;sup&gt;-2&lt;/sup&gt;s&lt;sup&gt;-1&lt;/sup&gt;</td>
<td>0.75</td>
<td>1.0</td>
<td>1.8</td>
<td>3.6</td>
</tr>
<tr>
<td><strong>Fraction of luminosity in top 1%</strong> L&lt;sub&gt;0.01/L&lt;/sub&gt;</td>
<td>87.1%</td>
<td>77.4%</td>
<td>58.3%</td>
<td>59.2%</td>
</tr>
</tbody>
</table>
The ILC

Status
- Technical Design Report now complete
- Decision point on moving forward has been reached

R&D
- Most significant R&D issues addressed during ILC Technical Design Phase [SRF cavity R&D, including industrialization; FLASH beam tests; damping ring studies, CESRTA; damping ring and beam delivery system studies at KEK-ATF]
- Some technical challenges remain (eg, complete ATF2 program), but no obvious showstoppers

Time
- Team ready to move forward with detailed engineering and site-specific design
- Timescale contingent on decision process and international support
CLIC layout at 500 GeV

Main beam – 1 A, 200 ns from 9 GeV to 1.5 TeV

Fig 3.2: Overview of the CLIC layout at $\sqrt{s} = 500$ GeV
# Potential Staged CLIC Parameters

<table>
<thead>
<tr>
<th>parameter</th>
<th>symbol</th>
<th>500</th>
<th>1400</th>
<th>3000</th>
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</thead>
<tbody>
<tr>
<td>centre of mass energy</td>
<td>( E_{\text{cm}} ) [GeV]</td>
<td>500</td>
<td>1400</td>
<td>3000</td>
</tr>
<tr>
<td>luminosity</td>
<td>( \mathcal{L} ) ( [10^{34} \text{ cm}^{-2}\text{s}^{-1}] )</td>
<td>2.3</td>
<td>3.2</td>
<td>5.9</td>
</tr>
<tr>
<td>luminosity in peak</td>
<td>( \mathcal{L}_{0.01} ) ( [10^{34} \text{ cm}^{-2}\text{s}^{-1}] )</td>
<td>1.4</td>
<td>1.3</td>
<td>2</td>
</tr>
<tr>
<td>gradient</td>
<td>( G ) ([\text{MV/m}])</td>
<td>80</td>
<td>80/100</td>
<td>100</td>
</tr>
<tr>
<td>site length</td>
<td>([\text{km}])</td>
<td>13</td>
<td>28</td>
<td>48.3</td>
</tr>
<tr>
<td>charge per bunch</td>
<td>( N ) ([10^9])</td>
<td>6.8</td>
<td>3.7</td>
<td>3.7</td>
</tr>
<tr>
<td>bunch length</td>
<td>( \sigma_z ) ([\mu\text{m}])</td>
<td>72</td>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td>IP beam size</td>
<td>( \sigma_x/\sigma_y ) ([\text{nm}])</td>
<td>200/2.26</td>
<td>( \approx 60/1.5 )</td>
<td>( \approx 40/1 )</td>
</tr>
<tr>
<td>norm. emittance</td>
<td>( \epsilon_x/\epsilon_y ) ([\text{nm}])</td>
<td>2400/25</td>
<td>660/20</td>
<td>660/20</td>
</tr>
<tr>
<td>bunches per pulse</td>
<td>( n_b )</td>
<td>354</td>
<td>312</td>
<td>312</td>
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<tr>
<td>distance between bunches</td>
<td>( \Delta_b ) ([\text{ns}])</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>repetition rate</td>
<td>( f_r ) ([\text{Hz}])</td>
<td>50</td>
<td>50</td>
<td>50</td>
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<tr>
<td>est. power cons.</td>
<td>( P_{\text{wall}} ) ([\text{MW}])</td>
<td>271</td>
<td>361</td>
<td>582</td>
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</table>
Linear Colliders with $E > 1$ TeV

- ILC is $~50$ km at $1$ TeV
  - Possible to consider higher gradient SCRF materials or PWFA boost
- CLIC design is aimed at upgradable design $\rightarrow 0.5$-$3$ TeV
  - Geographic gradient of 4x higher than ILC
- Advanced acceleration options (plasma, dielectric)
  - Plasma acceleration has made great progress however still huge challenges in beam quality and stability
  - Extremely low charge dielectric-laser accelerators may provide only reasonable parameters in multi-TeV regime
  - None of AARD options are close to being ready
- Some plasma and dielectric options act as transformers taking high power beams $\rightarrow$ high energy beams
  - Possible to develop upgrade options for ILC-like technology?
Concept of Beam-Driven Plasma Linac

- Concept for a 1 TeV plasma wakefield-based linear collider
  - Use conventional Linear Collider concepts for main beam and drive beam generation and focusing and PWFA for acceleration
    - Makes good use of PWFA R&D and 30 years of conventional rf R&D
  - Concept illustrates focus of PWFA R&D program
    - High efficiency
    - Emittance preservation
    - Positrons
  - Allows study of cost-scales for further optimization of R&D
Challenges for Positron Plasma Wakefield Acceleration

In a hollow channel plasma, the plasma electrons originate from the same initial radius, and receive a fast kick from the drive beam. They travel toward the beam axis and form a coherent accelerating and focusing wake for positron beam.
### Possible Linear Collider Parameters

<table>
<thead>
<tr>
<th>Case</th>
<th>0.5 TeV ILC</th>
<th>3 TeV CLIC</th>
<th>10 TeV Dielectric Beam Acc.</th>
<th>10 TeV Plasma Accelerator</th>
<th>10 TeV Dielectric Laser Acc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy per beam (TeV)</td>
<td>0.25</td>
<td>1.5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Luminosity (10^{34} cm^{-2}s^{-1})</td>
<td>2</td>
<td>6.4</td>
<td>49</td>
<td>71.4</td>
<td>105</td>
</tr>
<tr>
<td>Electrons per bunch (×10^9)</td>
<td>20</td>
<td>3.7</td>
<td>4</td>
<td>4</td>
<td>0.002</td>
</tr>
<tr>
<td>Rep. rate (Hz) / number / train</td>
<td>5 / 1312</td>
<td>50 / 312</td>
<td>50 / 416</td>
<td>17,000 / 1</td>
<td>25,000,000 / 1</td>
</tr>
<tr>
<td>Horizontal emittance γε_x (nm-rad)</td>
<td>10,000</td>
<td>660</td>
<td>1000</td>
<td>200</td>
<td>0.1</td>
</tr>
<tr>
<td>Vertical emittance γε_y (nm-rad)</td>
<td>30</td>
<td>20</td>
<td>10</td>
<td>200</td>
<td>0.1</td>
</tr>
<tr>
<td>β* x/y (mm)</td>
<td>11 / 0.2</td>
<td>4 / 0.1</td>
<td>10 / 0.1</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Horizontal beam size at IP σ_x (nm)</td>
<td>474</td>
<td>49</td>
<td>32</td>
<td>2</td>
<td>0.06</td>
</tr>
<tr>
<td>Vertical beam size at IP σ_y (nm)</td>
<td>3.8</td>
<td>1.0</td>
<td>0.3</td>
<td>2</td>
<td>0.06</td>
</tr>
<tr>
<td>Luminosity enhancement factor</td>
<td>1.6</td>
<td>1.9</td>
<td>1.9</td>
<td>1.35</td>
<td>6.05</td>
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<tr>
<td>Bunch length σ_z (µm)</td>
<td>300</td>
<td>50</td>
<td>20</td>
<td>1</td>
<td>335</td>
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<tr>
<td>Beamstrahlung parameter Γ</td>
<td>0.07</td>
<td>6.7</td>
<td>56</td>
<td>8980</td>
<td>0.4</td>
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<tr>
<td>Beamstrahlung photons per electron n_γ</td>
<td>1.7</td>
<td>1.5</td>
<td>1.4</td>
<td>3.67</td>
<td>0.5</td>
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<tr>
<td>Beamstrahlung energy loss δ_E (%)</td>
<td>4.3</td>
<td>33</td>
<td>37</td>
<td>48</td>
<td>4.3</td>
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<tr>
<td>Accelerating gradient (GV/m)</td>
<td>0.031</td>
<td>0.1</td>
<td>0.5</td>
<td>10</td>
<td>0.5</td>
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<tr>
<td>Average beam power (MW)</td>
<td>5.3</td>
<td>13.9</td>
<td>55</td>
<td>54</td>
<td>38</td>
</tr>
<tr>
<td>Wall plug power (MW)</td>
<td>200</td>
<td>568</td>
<td>~1200</td>
<td>~1200</td>
<td>~550</td>
</tr>
<tr>
<td>One linac length (km)</td>
<td>15.5</td>
<td>23.5</td>
<td>10</td>
<td>1.0</td>
<td>10.5</td>
</tr>
</tbody>
</table>

*ILC and CLIC parameters from design reports; 10 TeV DBA scaled from Wei Gai communication; 10 TeV DLA and Plasma Accelerator from 2010 ICUIL/ICFA Workshop*
## CLIC and Wakefield LCs

### Status
- CLIC Conceptual Design Report complete
- Wakefield Accelerator Concepts – Feasibility being assessed

### R&D
- CLIC: Focus on technology and advanced systems R&D
- Wakefield Accelerators:
  - Ability to accelerate positrons
  - Demonstration of multi-stage acceleration
  - Understanding the extrapolation of all parameters to the regimes required for HEP accelerator use (emittance preservation, achievable energy spread, beam loading, repetition rate)

### Time
- CLIC: Timescale dependent on finalized technical design and physics needs
- Wakefield LCs:
  - Expect non-HEP applications on the ~decade timescale
  - Collider R&D phase to fully assess feasibility is likely decades scale
  - First application might be an ILC “afterburner”
**γ−γ Collider Concepts**

- **γ−γ Higgs Factory** ($E_{CM}\sim160$ GeV, photons carry $\sim80\%$ of CM E) might represent a `low cost' option to demonstrate the technology.
- Relative to LC: No positrons, damping rings, bunch compressors, …
- Laser parameters are challenging; requires optical cavity schemes.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SAPPHiRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>80 GeV</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>100 MW</td>
</tr>
<tr>
<td>Polarization</td>
<td>80%</td>
</tr>
<tr>
<td>Ave Beam Current</td>
<td>0.32 mA</td>
</tr>
<tr>
<td>E-e- geometric luminosity</td>
<td>$2.2\times10^{34}$</td>
</tr>
<tr>
<td>Laser wavelength</td>
<td>351 nm</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>200 kHz</td>
</tr>
<tr>
<td>Laser pulse energy</td>
<td>$\sim5$ J</td>
</tr>
</tbody>
</table>

**CLICHÉ: CLIC Higgs Experiment**

- **Beam Energy**: 80 GeV
- **Power Consumption**: 100 MW
- **Polarization**: 80%
- **Ave Beam Current**: 0.32 mA
- **E-e- geometric luminosity**: $2.2\times10^{34}$
- **Laser wavelength**: 351 nm
- **Repetition rate**: 200 kHz
- **Laser pulse energy**: $\sim5$ J
\( \gamma-\gamma \) Colliders

**Status**
- Principal technical challenge is laser system
- Question: Would the community be interested in a standalone facility versus eventual companion capability with an \( e^+e^- \) LC? Can this provide the required physics?

**R&D**
- Validate feasibility of required laser – significant recent progress
- Would need to establish a full Technical Design

**Time**
- In principle, a decision point could be reached in a few years
Muon Accelerator Concepts

**Neutrino Factory**

- Proton Driver
- Accumulator
- Compressor
- Hg-Jet Target
- Capture Solenoid
- Target
- Decay Channel
- Buncher
- Phase Rotator
- Front End
- 4D Cooler
- Acceleration
  - 0.2–1.2 GeV
  - 1.2–5 GeV
- Accelerator Types:
  - Linac, Recirculating Linac (RLA) or FFAG
- Muon Storage Ring
  - 5 GeV
  - ≈0.35 km
- μ Factory Goal:
  - \( O(10^{21}) \) μ/yr within the accelerator acceptance

**Muon Collider**

- Proton Driver
- Accumulator
- Compressor
- Hg-Jet Target
- Capture Solenoid
- Target
- Decay Channel
- Buncher
- Phase Rotator
- Front End
- 6D Cooler
- Bunch
- Merge
- 6D Cooling
- Final Cooling
- Acceleration
  - Accelerator Types:
    - Linac, Recirculating Linacs (RLAs), Rapid Cycling Synchrotrons (RCS)
- Collider Ring
  - \( E_{\text{CoM}} \)
  - 126 GeV
  - 1.5 TeV
  - 3 TeV

**Goals:**

- ~126 GeV \( \rightarrow \) ~40,000 Higgs/yr
- Multi-TeV \( \rightarrow \) Lumi > \( 10^{34}\text{cm}^{-2}\text{s}^{-1} \)

**Major Challenges**
A Muon Accelerator Facility for Cutting Edge Physics on the Intensity and Energy Frontiers Based on Project X Stage II

- LBNE
- To SURF
- Buncher/Accumulator Rings
- Linac + RLA to ~5 GeV
- NF Decay Ring: \( \nu_s \) to SURF
- Front End + 4D + 6D
- RLA to 63 GeV + 300m Higgs Factory
- \( \nu \) STORM + Muon Beam R&D Facility
- Project X Stage III
- Project X Stage II
- vSTORM + Muon Beam R&D Facility

A 1.5 TeV collider would fit within the Tevatron ring
**MAP Designs for a Muon-Based Higgs Factory and Energy Frontier Colliders**

**Exquisite Energy Resolution Allows Direct Measurement of Higgs Width**

**Site Radiation mitigation with depth and lattice design: ≤ 10 TeV**

---

**Muon Collider Baseline Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Higgs Factory</th>
<th>Multi-TeV Baselines</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoM Energy</td>
<td>TeV</td>
<td>0.126</td>
<td>0.126</td>
</tr>
<tr>
<td>Avg. Luminosity</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>0.0017</td>
<td>0.008</td>
</tr>
<tr>
<td>Beam Energy Spread</td>
<td>%</td>
<td>0.003</td>
<td>0.004</td>
</tr>
<tr>
<td>Higgs/10$^7$sec</td>
<td></td>
<td>3,500</td>
<td>13,500</td>
</tr>
<tr>
<td>Circumference</td>
<td>km</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>No. of IPs</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>Hz</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>$\beta^*$</td>
<td>cm</td>
<td>3.3</td>
<td>1.7</td>
</tr>
<tr>
<td>No. muons/bunch</td>
<td>$10^{12}$</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>No. bunches/beam</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Norm. Trans. Emittance, $\varepsilon_{TN}$</td>
<td>$\pi$ mm-rad</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Norm. Long. Emittance, $\varepsilon_{LN}$</td>
<td>$\pi$ mm-rad</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>Bunch Length, $\sigma_b$</td>
<td>cm</td>
<td>5.6</td>
<td>6.3</td>
</tr>
<tr>
<td>Beam Size @ IP</td>
<td>$\mu$m</td>
<td>150</td>
<td>75</td>
</tr>
<tr>
<td>Beam-beam Parameter / IP</td>
<td></td>
<td>0.005</td>
<td>0.02</td>
</tr>
<tr>
<td>Proton Driver Power</td>
<td>MW</td>
<td>$4^{2}$</td>
<td>4</td>
</tr>
</tbody>
</table>

# Could begin operation with Project X Stage 2 beam

Success of advanced cooling concepts ⇒ several $\times 10^{32}$

---

Range of Top Params:

$\delta E/E \sim 0.01 - 0.1\%$

$L_{\text{avg}} \sim 0.7 - 6 \times 10^{33}$
Muon Colliders

Status

• MAP Feasibility Assessment underway

R&D

• Establishing Initial Baseline Design
• Technology R&D: Cooling channel hardware, RF in B-fields, high field magnets (synergistic with HE-LHC needs)
• Staging Study: Physics + R&D + Demos required for next stage
• Muon Ionization Cooling Experiment

Time

• Feasibility Assessment by end of decade
• Completion of MICE by end of decade
• NuMAX (initial long baseline NF): Informed Decision by ~2020
• Collider Program: Informed Decision by mid-2020s
CLOSING REMARKS

Long-Term Perspective

Conclusions
Some Connections…

• A theme that has arisen in the capabilities discussions has been that of upgrade paths
  – Note that a number of “constrained” options didn’t even get mention in this presentation

• There are many special synergies that also come into play:
  – TLEP and a ~100 TeV hadron collider
  – Muon Collider and the Neutrino Program
  – Technology linkages (eg, MAP and HE LHC magnet development)
  – γ−γ as a companion capability to an LC
  – A wakefield accelerator upgrade to a conventional LC
  – And this is not an exhaustive list…
Establishing A Long-Term Perspective

- Maintain Investment in World Class Domestic HEP Accelerator Capabilities and Infrastructure
- Nurture a Vibrant and Cutting Edge Accelerator R&D Program
- Develop the Next Generation(s) of Accelerator Specialists
- Support Strong Global Connections
- US-HEP Energy Frontier Research Program

July 30, 2013
Community Summer Study 2013 (CSS2013) - University of Minnesota
What do you get for a Billion Dollars?

NSLS-II: $0.9B, 0.8 km storage ring

SNS: $1.4B, 1 GeV Linac, Ring, high-power target, 1km
Jim Siegrist’s “Boundary Conditions”

- Note that a ‘brute force’ approach that seeks to spend vast sums in order to build some facility/physics capability simply will not work in today’s fiscal environment. This has been empirically demonstrated.
  - Most recently, via our discussions on LBNE, we have confirmed that single domestic project expenditures must be somewhat smaller than $1B per stage.

- CSS2013 participants are encouraged to think about whatever physics you think is most relevant and important to progress in HEP, but the effort you put in should be tempered with a realistic assessment of funding possibilities.
  - Many ideas can be staged to provide new physics capability at each step, but some cannot.

- Stringing together projects that build upon previous investments either scientifically or through recycling of infrastructure is generally well received.

- It’s imperative to make the case for the physics we need,
- But we must also develop a coherent plan that is realistic if we want to preserve the health and vitality of the U.S. HEP program
- The challenges for all of the options presented here go beyond the technical
Conclusions I

• The LHC program for the next 20 years is well-defined
  – Questions arise as to what comes next
    • For example: Is an investment in a facility such as TLEP desirable on the 10 year timescale because it can lead to a VHE-LHC/VLHC capability in ~30 years?

• There is little question that the ILC design is, at present, the most complete and well-studied design for a machine targeted at the Higgs
  – But, what will we do if the next round of LHC data finally shows something at > 1 TeV?
  – On the relevant timescale (assuming advances in the R&D program), we may want to consider comparisons such as the plot on the next page…
What is the comparison between TLEP with 2 IPs and ILC 250 at full power?
Conclusions II

• The necessity of US engagement in the ongoing LHC program is clear
• As is maintaining global connections if the next collider facility is off-shore
• At the same time we cannot ignore other elements of the US HEP program
  – Investing in our domestic facilities which support non-collider portions of HEP
  – Maintaining a robust R&D program which benefits both our global connections and can open the door to additional world class capabilities in the US
  – And continue to train the experts to support the next generation of facilities