A Circular e+e- Collider to Study H(125) Properties - Accelerator

Zimmermann, F (CERN)

17 June 2013

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A circular $e^+e^-$ collider to study $H(125)$ properties - accelerator

Frank Zimmermann

Frascati

14 February 2013

work supported by the European Commission under the FP7 Research Infrastructures project EuCARD, grant agreement no. 227579
outline

- motivation
- machine proposals
- parameters, lifetime, key concepts
- various features
- a long-term strategy
- HF quality indicators
- the path forward
circular HFs – a few examples

SuperTRISTAN in Tsukuba: 40 km

SLAC/LBNL design: 27 km

LEP3: 27 km
TLEP (LEP4): 80 km near Geneva

FNAL site filler, 16 km

LEP3: 27 km
TLEP (LEP4): 80 km near Geneva

K. Oide, KEK
A. Blondel, J. Osborne, F. Zimmermann

IHEP Chinese HF + Super pp Collider

50 or 70 km

Q. Qin, IHEP

e⁻ e⁺ Higgs Factory

T. Sen, E. Gianfelice-Wendt, Y. Alexahin, FNAL

SLAC/LBNL design: 27 km

Y. Cai, SLAC

FNAL site filler, 16 km

& FNAL VLLC 233 km ring

K. Oide, KEK
A. Blondel, J. Osborne, F. Zimmermann

IHEP Chinese HF + Super pp Collider

50 or 70 km

Q. Qin, IHEP

e⁻ e⁺ Higgs Factory

T. Sen, E. Gianfelice-Wendt, Y. Alexahin, FNAL
# LEP3, TLEP (LEP4)

\[(\text{e}^+\text{e}^-\rightarrow \text{ZH}, \text{e}^+\text{e}^- \rightarrow \text{W}^+\text{W}^-, \text{e}^+\text{e}^- \rightarrow \text{Z}, [\text{e}^+\text{e}^- \rightarrow \text{t\bar{t}}])\]

## Key Parameters

<table>
<thead>
<tr>
<th></th>
<th>LEP3</th>
<th>TLEP (LEP4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>26.7 km</td>
<td>80 km</td>
</tr>
<tr>
<td>Max beam energy</td>
<td>120 GeV</td>
<td>175 GeV</td>
</tr>
<tr>
<td>Max no. of IPs</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Luminosity at 350 GeV c.m.</td>
<td>-</td>
<td>0.7x10^{34} cm^{-2}s^{-1}</td>
</tr>
<tr>
<td>Luminosity at 240 GeV c.m.</td>
<td>10^{34} cm^{-2}s^{-1}</td>
<td>5x10^{34} cm^{-2}s^{-1}</td>
</tr>
<tr>
<td>Luminosity at 160 GeV c.m.</td>
<td>5x10^{34} cm^{-2}s^{-1}</td>
<td>2.5x10^{35} cm^{-2}s^{-1}</td>
</tr>
<tr>
<td>Luminosity at 90 GeV c.m.</td>
<td>2x10^{35} cm^{-2}s^{-1}</td>
<td>10^{36} cm^{-2}s^{-1}</td>
</tr>
</tbody>
</table>

at the \( Z \) pole repeating LEP physics programme in a few minutes...
circular HFs – beam lifetime

**LEP2:**
- beam lifetime $\sim 6$ h
- dominated by radiative Bhabha scattering with cross section $\sigma \sim 0.215$ barn

(H. Burkhardt)

**LEP3:**
- with $L \sim 10^{34}$ cm$^{-2}$s$^{-1}$ at each of several IPs:
  $\tau_{\text{beam, LEP3}} \sim 18$ minutes from rad. Bhabha scattering → solution: top-up injection (A. Blondel)
- additional beam lifetime limit due to beamstrahlung:
  (1) large momentum acceptance ($\eta \geq 3\%$), and/or
  (2) flat(ter) beams and/or
  (3) fast replenishing

(V. Telnov, K. Yokoya, M. Zanetti)
circular HFs – beamstrahlung

- simulation w 360M macroparticles
- $\tau$ varies exponentially w energy acceptance $\eta$
- post-collision $E$ tail $\rightarrow$ lifetime $\tau$

TLEP at 240 GeV:
- $\tau > 2$ s at $\eta = 1.0\%$ (4 IPs)
- $\tau > 37$ s at $\eta = 1.5\%$
- $\tau > 11$ min at $\eta = 2.0\%$
- $\tau > 3h$ at $\eta = 2.5\%$

TLEP at 350 GeV:
- $\tau > 6$ s at $\eta = 2.0\%$ (4 IPs)
- $\tau > 37$ s at $\eta = 2.5\%$
- $\tau > 3$ min at $\eta = 3.0\%$
- $\tau > 20$ min at $\eta = 3.5\%$
circular HFs – beamstrahlung

- simulation w 360M macroparticles
- $\tau$ varies exponentially w energy acceptance $\eta$
- post-collision $E$ tail $\rightarrow$ lifetime $\tau$

beam lifetime versus acceptance $\eta$ for 1 IP:
beamstrahlung luminosity spectrum

LEP3 & ILC:

- LEP3, $L_{0.01} = 1.0$
- ILC, $L_{0.01} = 0.86$

LEP3 beamstrahlung more benign than for linear collider
luminosity formulae & constraints

$$L = \frac{f_{\text{rev}} n_b N_b^2}{4\pi \sigma_x \sigma_y} = (f_{\text{rev}} n_b N_b) \left( \frac{N_b}{\varepsilon_x} \right) \frac{1}{4\pi} \frac{1}{\sqrt{\beta_x \beta_y}} \frac{1}{\sqrt{\varepsilon_y / \varepsilon_x}}$$

$$\left( f_{\text{rev}} n_b N_b \right) = \frac{P_{\text{SR}} \rho}{8.8575 \times 10^{-5} \frac{m}{\text{GeV}^{-3}} E^4} \text{ SR radiation power limit}$$

$$N_b = \frac{\xi_x 2\pi \gamma (1 + \kappa_\sigma)}{\rho_e} \text{ beam-beam limit}$$

$$\frac{N_b}{\varepsilon_x} = \frac{30 \gamma r_e^2}{\sigma_x \sigma_z \delta_{\text{acc}} \alpha} < 1 \text{ >30 min beamstrahlung lifetime (Telnov)} \rightarrow N_b, \beta_x$$

$$\rightarrow \text{minimize } \kappa_\varepsilon = \varepsilon_y / \varepsilon_x, \beta_y \sim \beta_x (\varepsilon_y / \varepsilon_x) \text{ and respect } \beta_y \geq \sigma_z$$
### LEP3/TLEP parameters -1

<table>
<thead>
<tr>
<th></th>
<th>LEP2</th>
<th>LHeC</th>
<th>LEP3</th>
<th>TLEP-Z</th>
<th>TLEP-H</th>
<th>TLEP-t</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy $E_b$ [GeV]</td>
<td>104.5</td>
<td>60</td>
<td>120</td>
<td>45.5</td>
<td>120</td>
<td>175</td>
</tr>
<tr>
<td>circumference [km]</td>
<td>26.7</td>
<td>26.7</td>
<td>26.7</td>
<td>80</td>
<td>80</td>
<td>80</td>
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<tr>
<td>beam current [mA]</td>
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<td>100</td>
<td>7.2</td>
<td>1180</td>
<td>24.3</td>
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<tr>
<td>#bunches/beam</td>
<td>4</td>
<td>2808</td>
<td>4</td>
<td>2625</td>
<td>80</td>
<td>12</td>
</tr>
<tr>
<td>#e-/beam $[10^{12}]$</td>
<td>2.3</td>
<td>56</td>
<td>4.0</td>
<td>2000</td>
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<td>horizontal emittance [nm]</td>
<td>48</td>
<td>5</td>
<td>25</td>
<td>30.8</td>
<td>9.4</td>
<td>20</td>
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<tr>
<td>vertical emittance [nm]</td>
<td>0.25</td>
<td>2.5</td>
<td>0.10</td>
<td>0.15</td>
<td>0.05</td>
<td>0.1</td>
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<tr>
<td>bending radius [km]</td>
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<td>2.6</td>
<td>9.0</td>
<td>9.0</td>
<td>9.0</td>
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<td>partition number $J_\varepsilon$</td>
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<td>1.5</td>
<td>1.5</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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<td>momentum comp. $\alpha_c [10^{-5}]$</td>
<td>18.5</td>
<td>8.1</td>
<td>8.1</td>
<td>9.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>SR power/beam [MW]</td>
<td>11</td>
<td>44</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
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<tr>
<td>$\beta_x^*$ [m]</td>
<td>1.5</td>
<td>0.18</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
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<tr>
<td>$\beta_y^*$ [cm]</td>
<td>5</td>
<td>10</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
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<tr>
<td>$\sigma_x^*$ [$\mu$m]</td>
<td>270</td>
<td>30</td>
<td>71</td>
<td>78</td>
<td>43</td>
<td>63</td>
</tr>
<tr>
<td>$\sigma_y^*$ [$\mu$m]</td>
<td>3.5</td>
<td>16</td>
<td>0.32</td>
<td>0.39</td>
<td>0.22</td>
<td>0.32</td>
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<tr>
<td>hourglass $F_{hg}$</td>
<td>0.98</td>
<td>0.99</td>
<td>0.59</td>
<td>0.71</td>
<td>0.75</td>
<td>0.65</td>
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<tr>
<td>$\Delta E_{SR}$ loss/turn [GeV]</td>
<td>3.41</td>
<td>0.44</td>
<td>6.99</td>
<td>0.04</td>
<td>2.1</td>
<td>9.3</td>
</tr>
</tbody>
</table>

**soon at SuperKEKB:**

$\beta_x^*=0.03 \, \text{m, } \beta_y^*=0.03 \, \text{cm}$

**SuperKEKB:** $\varepsilon_y/\varepsilon_x=0.25\%$
### LEP3/TLEP parameters -2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LEP2</th>
<th>LHeC</th>
<th>LEP3</th>
<th>TLEP-Z</th>
<th>TLEP-H</th>
<th>TLEP-t</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{RF,\text{tot}}$ [GV]</td>
<td>3.64</td>
<td>0.5</td>
<td>12.0</td>
<td>2.0</td>
<td>6.0</td>
<td>12.0</td>
</tr>
<tr>
<td>$\delta_{\text{max,RF}}$ [%]</td>
<td>0.77</td>
<td>0.66</td>
<td>5.7</td>
<td>4.0</td>
<td>9.4</td>
<td>4.9</td>
</tr>
<tr>
<td>$\xi_x$/IP</td>
<td>0.025</td>
<td>N/A</td>
<td>0.09</td>
<td>0.12</td>
<td>0.10</td>
<td>0.05</td>
</tr>
<tr>
<td>$\xi_y$/IP</td>
<td>0.065</td>
<td>N/A</td>
<td>0.08</td>
<td>0.12</td>
<td>0.10</td>
<td>0.05</td>
</tr>
<tr>
<td>$f_s$ [kHz]</td>
<td>1.6</td>
<td>0.65</td>
<td>2.19</td>
<td>1.29</td>
<td>0.44</td>
<td>0.43</td>
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<tr>
<td>$E_{\text{acc}}$ [MV/m]</td>
<td>7.5</td>
<td>11.9</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>eff. RF length [m]</td>
<td>485</td>
<td>42</td>
<td>600</td>
<td>100</td>
<td>300</td>
<td>600</td>
</tr>
<tr>
<td>$f_{RF}$ [MHz]</td>
<td>352</td>
<td>721</td>
<td>700</td>
<td>700</td>
<td>700</td>
<td>700</td>
</tr>
<tr>
<td>$\delta_{SR}$ rms [%]</td>
<td>0.22</td>
<td>0.12</td>
<td>0.23</td>
<td>0.06</td>
<td>0.15</td>
<td>0.22</td>
</tr>
<tr>
<td>$\sigma_{SR,z,rms}$ [cm]</td>
<td>1.61</td>
<td>0.69</td>
<td>0.31</td>
<td>0.19</td>
<td>0.17</td>
<td>0.25</td>
</tr>
<tr>
<td>$L/IP[10^{32}\text{cm}^{-2}\text{s}^{-1}]$</td>
<td>1.25</td>
<td>N/A</td>
<td>94</td>
<td>10335</td>
<td>490</td>
<td>65</td>
</tr>
<tr>
<td>number of IPs</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Rad.Bhabha b.lifetime [min]</td>
<td>360</td>
<td>N/A</td>
<td>18</td>
<td>74</td>
<td>32</td>
<td>54</td>
</tr>
<tr>
<td>$\gamma_{BS}$ [$10^{-4}$]</td>
<td>0.2</td>
<td>0.05</td>
<td>9</td>
<td>4</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>$n_y$/collision</td>
<td>0.08</td>
<td>0.16</td>
<td>0.60</td>
<td>0.41</td>
<td>0.50</td>
<td>0.51</td>
</tr>
<tr>
<td>$\Delta E_{BS}$/collision [MeV]</td>
<td>0.1</td>
<td>0.02</td>
<td>31</td>
<td>3.6</td>
<td>42</td>
<td>61</td>
</tr>
<tr>
<td>$\Delta E_{BS,rms}$/collision [MeV]</td>
<td>0.3</td>
<td>0.07</td>
<td>44</td>
<td>6.2</td>
<td>65</td>
<td>95</td>
</tr>
<tr>
<td>critical SR energy [MeV]</td>
<td>0.81</td>
<td>0.18</td>
<td>1.47</td>
<td>0.02</td>
<td>0.43</td>
<td>1.32</td>
</tr>
</tbody>
</table>

LEP data for 94.5 - 101 GeV consistently suggest a beam-beam limit of ~0.115 (R.Assmann, K. C.)
circular HFs – arc lattice

SuperT40_SLC_3_trim_2.sad

KEK design

IHEP design

Q. Qin

K. Oide

SLAC/LBNL design

FNAL site filler

T. Sen, E. Gianfelice-Wendt, Y. Alexahin
circular HFs – final-focus design

KEK design

IHEP design

SLAC/LBNL design

FNAL site filler
circular HFs - momentum acceptance

KEK design before optics correction

±1.1%

SLAC/LBNL design

±2.0%

KEK design after optics correction

±1.3%

FNAL site filler

±1.6%

T. Sen, E. Gianfelice-Wendt, Y. Alexahin
circular HFs – top-up injection

double ring with top-up injection

supports short lifetime & high luminosity

top-up experience: PEP-II, KEKB, light sources
**top-up injection**

**SPS as LEP injector** accelerated $e^\pm$ from 3.5 to 20 GeV (later 22 GeV) on a very short cycle: acceleration time = 265 ms or about 62.26 GeV/s


assuming injection from the SPS into the top-up accelerator at the same energy of 20 GeV and final energy of 120 GeV: acceleration time = 1.6 seconds

total cycle time = **10 s** looks conservative (→ **refilling** ~1% of the LEP3 beam, for $\tau_{\text{beam}}$ ~16 min)
top-up injection: schematic cycle

beam current in collider (15 min. beam lifetime)

energy of accelerator ring

120 GeV

20 GeV

10 s
top-up injection at PEP-II/BaBar

Before Top-Up Injection

After Top-Up Injection

average ≈ peak luminosity (H≈1)!

PEP-II: Luminosity and beam currents for a 24-hour period (a) before and (b) after the implementation of trickle injection.
Top-up injection will work for a Circular Higgs Factory.

A full energy injector is needed.

A synchrotron injector will work the best, but is more than is needed (60 Hz!).

A rapidly ramped storage ring is likely adequate (4 sec).

The detectors will need to mask out the buckets with damping injected bunches during data taking as had been done for PEP-II/BaBar:

**BaBar trigger masking:**
Mask all of ring a few tens of turns.
Mask injected bunch area for 1250 turns or about 0.9 msec.
for one day (July 3, 2006): \( H \approx 0.95 \)
for one month (August 2007): \( H \approx 0.63 \)
Circular Collider & SR Experience

3rd generation light sources

<table>
<thead>
<tr>
<th>Year</th>
<th>Source</th>
<th>Country</th>
<th>Energy (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>ESRF, France (EU)</td>
<td>France</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>ALS, US</td>
<td>US</td>
<td>3.5-1.9</td>
</tr>
<tr>
<td>1993</td>
<td>TLS, Taiwan</td>
<td>Taiwan</td>
<td>1.5</td>
</tr>
<tr>
<td>1994</td>
<td>ELETTRA, Italy</td>
<td>Italy</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>ALS, Korea</td>
<td>Korea</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>MAX II, Sweden</td>
<td>Sweden</td>
<td>1.5</td>
</tr>
<tr>
<td>1996</td>
<td>APS, US</td>
<td>US</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>LNLS, Brazil</td>
<td>Brazil</td>
<td>1.35</td>
</tr>
<tr>
<td>1997</td>
<td>Spring-8, Japan</td>
<td>Japan</td>
<td>8</td>
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<tr>
<td></td>
<td>ESSY II, Germany</td>
<td>Germany</td>
<td>1.9</td>
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<tr>
<td>2000</td>
<td>ANKA, Germany</td>
<td>Germany</td>
<td>2.5</td>
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<tr>
<td></td>
<td>SLS, Switzerland</td>
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<td>2.4</td>
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<td>US</td>
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<td>CLS, Canada</td>
<td>Canada</td>
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<td>France</td>
<td>2.8</td>
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<td>DIAMOND, UK</td>
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<td></td>
<td>ASP, Australia</td>
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<td>MAX III, Sweden</td>
<td>Sweden</td>
<td>700 MeV</td>
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<td></td>
<td>Indus-II, India</td>
<td>India</td>
<td>2.5</td>
</tr>
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<td></td>
<td>SSRF, China</td>
<td>China</td>
<td>3.4</td>
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<td>PETRA-III, Germany</td>
<td>Germany</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>ALBA, Spain</td>
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</tr>
</tbody>
</table>

well understood technology & typically exceeding design performance within a few years
Emittances in Circular Colliders & Modern Light Sources

Top up injection essential for achieving small vertical emittance

Lenny Rivkin, 2nd LEP3 Day

R. Bartolini, DIAMOND
circular HFs: synchrotron-radiation heat load

<table>
<thead>
<tr>
<th></th>
<th>PEP-II</th>
<th>SPEAR3</th>
<th>LEP3</th>
<th>TLEP-Z</th>
<th>TLEP-H</th>
<th>TLEP-t</th>
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</thead>
<tbody>
<tr>
<td>E (GeV)</td>
<td>9</td>
<td>3</td>
<td>120</td>
<td>45.5</td>
<td>120</td>
<td>175</td>
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<tr>
<td>I (A)</td>
<td>3</td>
<td>0.5</td>
<td>0.0072</td>
<td>1.18</td>
<td>0.0243</td>
<td>0.0054</td>
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<td>rho (m)</td>
<td>165</td>
<td>7.86</td>
<td>2625</td>
<td>9000</td>
<td>9000</td>
<td>9000</td>
</tr>
<tr>
<td>Linear Power (W/cm)</td>
<td>101.8</td>
<td>92.3</td>
<td>30.5</td>
<td>8.8</td>
<td>8.8</td>
<td>8.8</td>
</tr>
</tbody>
</table>

LEP3 and TLEP have 3-10 times less SR heat load per meter than PEP-II or SPEAR! (though higher photon energy)

N. Kurita, U. Wienands, SLAC
TLEP polarization


“... by adopting the levels of alignment that are now standard for synchrotron-radiation sources and by applying harmonic closed-orbit spin matching, there is reason to hope that high polarisation in a flat ring can ... be obtained”
TLEP3 key components

- tunnel
- SRF system
- cryoplants
- magnets
- injector ring
- detectors

tunnel is main cost:
3x LEP tunnel = 2.1 BCHF
9x LHeC tunnel cost estimate = 2.25 BCHF
inofficial/official TLEP tunnel cost ~2.5 BCHF
TLEP3 key issues

- SR handling and radiation shielding
- Optics effect energy sawtooth
  [separate arcs?! (K. Oide)]
- Beam-beam interaction for large $Q_s$ and significant hourglass effect
- IR design with even larger momentum acceptance
- Integration in LHC tunnel (LEP3)
- Pretzel scheme for TERA-Z operation?
- Impedance effects for high-current running at Z pole
NEUTRON PRODUCTION BY LEP SYNCHROTRON RADIATION USING EGS

W.R. Nelson and J.W.N. Tuyn

Fig. 2. Synchrotron Radiation Spectrum from LEP

\[ E = 130 \text{ GeV} \]
\[ i = 1.0 \text{ mA} \]
\[ R = 3544.5 \text{ m} \]

\[ \frac{dN}{dE} \text{ (n/MeV-sec per meter of beam)} \]

- Exact Spectrum
- Sampled Spectrum

Neutron Production by LEP Synchrotron Radiation Using EGS

W.R. Nelson and J.W.N. Tuyn

\[ \text{Threshold Energies} \]

\[ \text{Pb-206, Pb-207, Pb-208, Ca-43, Ca-45, Al-27} \]
transverse impedance & TMCI

**LEP** bunch intensity was limited by TMCI: \( N_{b,\text{thr}} \sim 5 \times 10^{11} \) at 22 GeV

**LEP3** with 700 MHz: **at 120 GeV we gain a factor 5.5 in the threshold**, which almost cancels a factor \((0.7/0.35)^3 \sim 8\) arising from the change in wake-field strength due to the different RF frequency

**LEP3** \( Q_s \sim 0.2 \), **LEP** \( Q_s \sim 0.15 \): further **25% increase** in TMCI threshold?

**only ½ of LEP transverse kick factor came from SC RF cavities**

**LEP3 beta functions at RF cavities** might be smaller than in LEP

**LEP3 bunch length (2-3 mm) is shorter** than at LEP injection (5-9 mm)

M. Lamont, SL-Note-98-026 (OP)
Circular & Linear HF: peak luminosity vs energy

Example with
- $\eta = 2\%$
- $\xi_y = 0.15$
- $\varepsilon_{gy} = 0.1\text{nm}$

**LEP3/TLEP would be THE choice for $e^+e^-$ collision energies up to $\sim 370$ GeV**
<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>vertical rms IP spot sizes in nm</strong></td>
<td></td>
</tr>
<tr>
<td>LEP2</td>
<td>3500</td>
</tr>
<tr>
<td>KEKB</td>
<td>940</td>
</tr>
<tr>
<td>SLC</td>
<td>500</td>
</tr>
<tr>
<td><strong>LEP3</strong></td>
<td>320</td>
</tr>
<tr>
<td><strong>TLEP-H</strong></td>
<td>220</td>
</tr>
<tr>
<td><strong>ATF2, FFTB</strong></td>
<td>72 (35), 65</td>
</tr>
<tr>
<td><strong>SuperKEKB</strong></td>
<td>50</td>
</tr>
<tr>
<td><strong>SAPPHiRE</strong></td>
<td><strong>18</strong></td>
</tr>
<tr>
<td><strong>ILC</strong></td>
<td>5 – 8</td>
</tr>
<tr>
<td><strong>CLIC</strong></td>
<td>1 – 2</td>
</tr>
</tbody>
</table>

- in regular font: achieved
- in italics: design values

$\beta_y^* \rightarrow 5 \text{ cm} \rightarrow 1 \text{ mm}$

**LEP3/TLEP will learn from ATF2 & SuperKEKB**
recent comment by eminent German particle physicist: “TLEP is much riskier and its performance highly uncertain; while the ILC performance numbers are very conservative” [?]

extrapolation from past experience

<table>
<thead>
<tr>
<th></th>
<th>LEP2→TLEP-H</th>
<th>SLC→ILC 250</th>
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<tbody>
<tr>
<td>peak luminosity</td>
<td>x400</td>
<td>x2500</td>
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<tr>
<td>energy</td>
<td>x1.15</td>
<td>x2.5</td>
</tr>
<tr>
<td>vertical geom. emittance</td>
<td>x1/5</td>
<td>x1/400</td>
</tr>
<tr>
<td>vert. IP beam size</td>
<td>x1/15</td>
<td>x1/150</td>
</tr>
<tr>
<td>e&lt;sup&gt;+&lt;/sup&gt; production rate</td>
<td>x1/2 !</td>
<td>x65</td>
</tr>
<tr>
<td>commissioning time</td>
<td>&lt;1 year → ?</td>
<td>&gt;10 years → ?</td>
</tr>
</tbody>
</table>
**a glance at LHC & LHC upgrades**

**LHC is the 1st Higgs factory!**

\[ E_{\text{CoM}} = 8-14 \text{ TeV}, \hat{L} \approx 10^{34} \text{cm}^{-2}\text{s}^{-1} \]

total cross section at 8 TeV: 22 pb

1 M Higgs produced so far – more to come

15 H bosons / min – and more to come

\[ 8 \rightarrow 14 \text{ TeV}: \text{ggH} \times 1.5 \quad \text{F. Cerutti, P. Janot} \]

**HE-LHC:** in LHC tunnel (2035-)

\[ E_{\text{CoM}} = 33 \text{ TeV}, \hat{L} = 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \]

**HL-LHC** (~2022-2030)

will deliver ~9x more H bosons!

\[ E_{\text{CoM}} = 14 \text{ TeV}, \hat{L} = 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \]

with luminosity leveling

**VHE-LHC:** new 80 km tunnel

\[ E_{\text{CoM}} = 84-104 \text{ TeV}, \hat{L} = 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \]

**20-T dipole magnet**

16 T magnets over 80 km (Ex6) likely “easier” than 20 T magnets over 27 km (Ex2.5)!

E. Todesco, L. Rossi, P. McIntyre

J. Osborne, C. Waaijer, S. Myers
possible long-term strategy

TLEP (80 km, $e^+e^-$, up to ~350 GeV c.m.)
VHE-LHC (pp, up to 100 TeV c.m.)

same detectors!

also: $e^+ (120 \text{ GeV}) - p (7 \& 50 \text{ TeV})$ collisions

≥50 years of $e^+e^-, pp, ep/A$ physics at highest energies
parameters for **LHC**, **HL-LHC**, **HE-LHC** and **VHE-LHC** (examples)

<table>
<thead>
<tr>
<th>parameter</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>HE-LHC</th>
<th>VHE-LHC</th>
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</thead>
<tbody>
<tr>
<td>c.m. energy [TeV]</td>
<td>14</td>
<td>14</td>
<td>33</td>
<td>100</td>
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<tr>
<td>circumference C [km]</td>
<td>26.7</td>
<td>26.7</td>
<td>26.7</td>
<td>80</td>
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<tr>
<td>dipole field [T]</td>
<td>8.33</td>
<td>8.33</td>
<td>20</td>
<td>20</td>
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<td>dipole coil aperture [mm]</td>
<td>56</td>
<td>56</td>
<td>40</td>
<td>40</td>
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<tr>
<td>beam half aperture [cm]</td>
<td>~2</td>
<td>~2</td>
<td>1.3</td>
<td>1.3</td>
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<tr>
<td>injection energy [TeV]</td>
<td>0.45</td>
<td>0.45</td>
<td>&gt;1.0</td>
<td>7.0</td>
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<tr>
<td>no. of bunches $n_b$</td>
<td>2808</td>
<td>2808</td>
<td>1404</td>
<td>4210</td>
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<tr>
<td>bunch population $N_b [10^{11}]$</td>
<td>1.125</td>
<td>2.2</td>
<td>1.62</td>
<td>1.59</td>
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<td>init. transv. norm. emit. [µm]</td>
<td>3.73</td>
<td>2.5</td>
<td>2.10</td>
<td>3.37</td>
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<td>initial longitudinalemit. [eVs]</td>
<td>2.5</td>
<td>2.5</td>
<td>5.67</td>
<td>17.2</td>
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<td>no. IPs contributing to tune shift</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<tr>
<td>max. total beam-beam time shift</td>
<td>0.01</td>
<td>0.015</td>
<td>0.01</td>
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<td>beam circulating current [A]</td>
<td>0.584</td>
<td>1.12</td>
<td>0.412</td>
<td>0.401</td>
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<tr>
<td>rms bunch length [cm]</td>
<td>7.55</td>
<td>7.55</td>
<td>7.7</td>
<td>7.7</td>
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<tr>
<td>IP beta function [m]</td>
<td>0.55</td>
<td>0.15</td>
<td>0.3</td>
<td>0.9</td>
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<tr>
<td>init. rms IP spot size [µm]</td>
<td>16.7</td>
<td>7.1</td>
<td>6.0</td>
<td>7.5</td>
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<td>full crossing angle [µrad]</td>
<td>285</td>
<td>590</td>
<td>240</td>
<td>100</td>
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<td>stored beam energy [MJ]</td>
<td>362</td>
<td>694</td>
<td>601</td>
<td>5410</td>
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<td>SR power per ring [kW]</td>
<td>3.6</td>
<td>6.9</td>
<td>82.5</td>
<td>2356</td>
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<td>arc SR heat load $dW/ds$ [W/m]</td>
<td>0.21</td>
<td>0.40</td>
<td>3.5</td>
<td>99</td>
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<td>energy loss per turn [keV]</td>
<td>6.7</td>
<td>6.7</td>
<td>201.3</td>
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<td>critical photon energy [eV]</td>
<td>44</td>
<td>44</td>
<td>575</td>
<td>5474</td>
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<tr>
<td>photon flux $[10^{17}/m/s]$</td>
<td>1.0</td>
<td>1.9</td>
<td>1.6</td>
<td>1.3</td>
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<td>longit. SR emit. damping time [h]</td>
<td>12.9</td>
<td>12.9</td>
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<td>horiz. SR emit. damping time [h]</td>
<td>25.8</td>
<td>25.8</td>
<td>2.0</td>
<td>0.64</td>
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<td>init. longit. IBS emit. rise time [h]</td>
<td>57</td>
<td>21.0</td>
<td>77</td>
<td>634</td>
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<tr>
<td>init. horiz. IBS emit. rise time [h]</td>
<td>103</td>
<td>15.4</td>
<td>40</td>
<td>306</td>
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<tr>
<td>peak events per crossing</td>
<td>19</td>
<td>140 (lev.)</td>
<td>190</td>
<td>190</td>
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<tr>
<td>peak luminosity $[10^{34} \text{ cm}^{-2} \text{s}^{-1}]$</td>
<td>1.0</td>
<td>7.4</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>beam lifetime due to burn off [h]</td>
<td>45</td>
<td>11.6</td>
<td>6.3</td>
<td>18.6</td>
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<tr>
<td>optimum run time [h]</td>
<td>15.2</td>
<td>8.9</td>
<td>6.5</td>
<td>12.2</td>
</tr>
<tr>
<td>opt. av. int. luminosity / day [fb^{-1}]</td>
<td>0.47</td>
<td>3.7</td>
<td>1.5</td>
<td>2.3</td>
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<td>collider parameters</td>
<td>TLHeC</td>
<td>VHE-TLHeC</td>
<td></td>
<td></td>
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<tr>
<td>--------------------------</td>
<td>-----------</td>
<td>-----------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>species</td>
<td>$e^\pm$</td>
<td>$p$</td>
<td>$e^\pm$</td>
<td>$p$</td>
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<tr>
<td>beam energy [GeV]</td>
<td>120</td>
<td>7000</td>
<td>120</td>
<td>500000</td>
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<td>bunch spacing [µs]</td>
<td>3</td>
<td>3</td>
<td>3</td>
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<tr>
<td>bunch intensity [10^{11}]</td>
<td>5</td>
<td>3.5</td>
<td>5</td>
<td>3.5</td>
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<tr>
<td>beam current [mA]</td>
<td>24.3</td>
<td>51.0</td>
<td>24.3</td>
<td>51.0</td>
</tr>
<tr>
<td>rms bunch length [cm]</td>
<td>0.17</td>
<td>4</td>
<td>0.17</td>
<td>2</td>
</tr>
<tr>
<td>rms emittance [nm]</td>
<td>10,2</td>
<td>0.40</td>
<td>10,2</td>
<td>0.06</td>
</tr>
<tr>
<td>$\beta_{x,y}$ [cm]</td>
<td>2,1</td>
<td>60,5</td>
<td>0.5,0.25</td>
<td>60,5</td>
</tr>
<tr>
<td>$\sigma_{x,y}$ [µm]</td>
<td>15, 4</td>
<td></td>
<td>6, 2</td>
<td></td>
</tr>
<tr>
<td>beam-beam parameter $\xi$</td>
<td>0.05, 0.09</td>
<td><strong>0.03,0.01</strong></td>
<td>0.07,0.10</td>
<td><strong>0.03,0.007</strong></td>
</tr>
<tr>
<td>hourglass reduction</td>
<td>0.63</td>
<td></td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td>CM energy [TeV]</td>
<td>1.8</td>
<td></td>
<td>4.9</td>
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<tr>
<td>luminosity [10^{34}cm^{-2}s^{-1}]</td>
<td>0.5</td>
<td></td>
<td>1.6</td>
<td></td>
</tr>
</tbody>
</table>
arrangement in VHE-LHC tunnel

Lucio Rossi
CLIC workshop
28 Jan. 2013

VHE-LHC injector ring “LER”
(using transmission line magnet)

30 mm V gap
50 mm H gap
Bin = 0.5 T
Bextr = 1.5 T

HE-LHC’10, p. 101
VHE-LHC’s LER magnets compatible with TLEP and VLHeC – 100 MW SR

advantages:
- cheap, like resistive magnets
- central gap could be shortcircuited
- magnets separated: provides electrons at 120 GeV and protons at 5 TeV/beam
- limited cryopower (HTS) in shadow of SCRF cavities
- SC cables developed already for SC links (HiLumi) and power applications
- SR taken at 300 K
Lucio Rossi’s «plan for all»

<table>
<thead>
<tr>
<th>Year</th>
<th>Proto &amp; Indust.</th>
<th>Constr. &amp; Install.</th>
<th>Physics</th>
<th>LHC</th>
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<tbody>
<tr>
<td>1995</td>
<td></td>
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</tr>
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<td>2000</td>
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<td>2005</td>
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<td>2015</td>
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<td>2020</td>
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<td>2025</td>
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<td>2050</td>
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<td>2055</td>
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</tbody>
</table>

**HL-LHC**
- Study-R&D
- Proto & Indust.
- Constr & Install.
- Physics

**HE-LHC**
- Study-R&D
- Proto & Indust.
- Constructions and Installation
- Physics

**VHE-LHC + leptons**
- Study - R&D
- Tunnel construction
- Install LER
- Physics
- TLEP
- LHeC
- Constr. and Install. VHE
- Physics VHE

2017-2020 is critical time!

According to Physics needs, the 80 km tunnel can:
- be alternative to HE-LHC
- or be complementary to HE-LHC
- accommodate at negligible extra-cost TLEP and VLHeC
- modular detector design allows evolution from TLEP-H/TLHeC to VHE-LHC
If what you have done yesterday still looks big to you, you haven’t done much today.
maximum TLEP luminosity

maximum theoretical luminosity is

\[ L = \left( \frac{f_{\text{rev}} n_b N_b}{2} \right) \frac{\gamma}{r_e} \frac{\xi_y}{\beta_y^*} R_{\text{hourglass}} \]

\[ = 1.7 \times 10^{16} \times \rho [\text{km}] \]

total power limit (100 MW SR)

Max. of 0.1

Beam-beam limit

For LEP3 this is 6 cm\(^{-1}\) (0.6/0.1 cm\(^{-1}\)). For TLEP =0.75/0.1 cm\(^{-1}\). Difficult to go beyond this without nanobeam /crab-waist scheme

\[ L_{\text{max}} = 4.3 \times 10^{33} cm^{-1}s^{-1} \times \rho [\text{km}] \]
even higher TLEP luminosity?

• charge compensation (CC) – counteracting the electric field of the incoming beam by a second beam of opposite charge
• 4-beam collisions at DCI, Orsay, 1971
  - not a spectacular success
• new idea (V. Telnov, M. Koratzinos): use charge compensation to suppress beamstrahlung and push luminosity in crab-waist scheme
artist’s impression of CC-TLEP

- main ring magnets
- Thermal power management
- Vacuum management
- Vacuum chamber
- Accelerator ring magnets
- Clockwise e+
  - anticlockwise e-
- Clockwise e-
  - anticlockwise e+
Valery Telnov’s estimate for CC TLEP

\[
\frac{\Delta N}{N} = \left( \frac{\xi_c}{\xi_{nc}} \right)^{1/2} \left( \frac{L_c}{L_{nc}} \right)^{3/2}
\]

here

- c-charge compensated
- nc-noncompensated

The above consideration shows that the increase of the luminosity by a factor of 10 looks possible for all energies above \(2E=240\) GeV. A possible gain could reach a factor 25-40 for \(2E=400-500\), but this requires unrealistically high degree of neutralization (< 0.5-1%).

Scheme of a charge compensated crab-waist e+e- ring collider
HF quality indicators

- readiness / maturity
- cost, electrical power
- peak luminosity, #IPs
- integrated luminosity
  - Hübner $(H)$ factor = integrated lumi/(peak lumi \times calendar time for physics)
    \[ H_{\text{LEP}} \approx 0.2, \ H_{\text{LHC}} \approx 0.2, \ H_{\text{KEKB}} \approx 0.7, \ H_{\text{PEP-II}} \approx 0.7 \]
- commissioning time
- expandability
## HF Accelerator Quality (My Opinion)

<table>
<thead>
<tr>
<th></th>
<th>Linear C.</th>
<th>Circular C.</th>
<th>LHeC</th>
<th>Muon C.</th>
<th>$\gamma-\gamma$ C.</th>
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<tbody>
<tr>
<td>maturity</td>
<td>☻ ☻ ☻ ☻ ☻</td>
<td>☻ ☻ ☻ ☻ ☻</td>
<td>☻ ☻ ☻</td>
<td>☻ ☻ ☻</td>
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<td>size</td>
<td>☻ ☻ ☻ ☻ ☻</td>
<td>☻ ☻ ☻ ☻ ☻</td>
<td>☻ ☻ ☻</td>
<td>☻ ☻ ☻</td>
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<tr>
<td>cost</td>
<td>☻ ☻ ☻ ☻ ☻</td>
<td>☻ ☻ ☻ ☻ ☻</td>
<td>☻ ☻ ☻</td>
<td>☻ ☻ ☻</td>
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<td>#IPs</td>
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<td>4</td>
<td>1</td>
<td>1</td>
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<tr>
<td>com. time</td>
<td>10 yr</td>
<td>2 yr</td>
<td>2 yr</td>
<td>10 yr</td>
<td>5 yr</td>
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<tr>
<td>$H$ factor</td>
<td>0.2 (SLC)</td>
<td>0.5 (1/2 PEP-II)</td>
<td>0.2?</td>
<td>0.1?</td>
<td>0.1?</td>
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<tr>
<td>Higgs/IP/yr</td>
<td>7 k [10 k]</td>
<td>20-100 k</td>
<td>5 k</td>
<td>5 k</td>
<td>10 k</td>
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<tr>
<td>expandability</td>
<td>1-3TeV $e^+e^-$, $\gamma\gamma$ C.</td>
<td>100 TeV $pp$</td>
<td>$\gamma\gamma$ C.</td>
<td>10 TeV $\mu\mu$</td>
<td>LC later</td>
</tr>
</tbody>
</table>

Inspired by S. Henderson, FNAL
the path forward

• set up international collaboration(s) & work structure
  – ERC proposal on large-acceptance IR design by Rogelio Tomas
  – TLEP Design Study Proposal for ECFA
  – INFN-LNF could play a key role!

• goal: publish TLEP Conceptual Design Study Report by end of 2014!
ERC Consolidation Grant Proposal “LEAF” – Draft

PL: Rogelio Tomas

includes international network for feeding new ideas, guidance, local support for experimental tests, review & collaboration

**LEAF**

Design of low-beta* insertions with extremely large (>3%) momentum acceptance for a future Higgs factory

A unique Higgs-like particle has been discovered in 2012 by two LHC experiments. This has triggered recent proposals for highest-energy circular e+e- colliders which could explore this novel particle with unprecedented luminosity thanks to vertical beam sizes of a few 100 nm at the Interaction Point (IP), requiring about a factor 50 lower vertical beta function at the collision point than LEP2, the highest-energy lepton collider operated so far, and at least 15% more energy. The performance of such machines may be restricted by the effect of “beamstrahlung” (synchrotron radiation in the field of the opposing beam emitted during the collision) together with a limited momentum acceptance, i.e. the off-momentum dynamic aperture, which represents a completely novel type of lifetime limitation for a storage-ring collider. The ultimate luminosity which can be achieved in a circular Higgs factory is directly related to the off-momentum dynamic aperture over a radiation damping time (typically 10-100 turns for the machines considered). The goal of the proposed project is to develop a low-beta* interaction region (IR) for a storage-ring collider, such that particles with an energy error of 3% or more, suddenly introduced by the emission of high energetic beamstrahlung photons, survive over 10 to 100 turns until they are damped back to the core of the beam thanks to the strong synchrotron radiation in the arcs. The luminosity of circular Higgs factories is directly related to off-momentum dynamic aperture. The proposed study will explore a large set of modifications to established final-focus designs together with additional non-linear elements in the collider arcs to control possible remaining aberrations. The new IR concepts and designs derived for this circular machine are likely to generate significant spin off, for example design and performance improvements for linear colliders, muon storage rings, light sources, and medical accelerators. In particular, there is a strong synergy with the laser-beam collision interaction region in the Compton storage ring for a polarized positron source. In the case of the Compton-scattering based intense positron source, electrons circulating in the Compton ring undergo large energy changes when they collide with a laser beam at a focal point.

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1 Instructions for completing Part B1 can be found in the Guide for Applicants for the Consolidator Grant 2013 Call.
draft work topics: TLEP accelerator

- parameter optimization with regard to lifetime and luminosity, at different energies, & different tunnels
- RF system design, prototyping & integration for collider and accelerator ring
- optics design for collider ring including low-beta IRs, off-momentum dynamic aperture, different energies
- beamstrahlung: lifetime, steady state beam distribution, dependence on tune etc.
- beam-beam interaction with large hourglass effect
- emittance tuning studies, errors, tolerances, etc.
- optics design and beam dynamics for the accelerator ring, ramping speed etc
- impedance budget, CSR, instabilities
- cryogenics system design
- magnets design: collider ring dipole, accelerator ring dipole, low-beta quadrupole
- radiation, shielding, cooling for 100 MW SR power
- vacuum system design
- engineering study of 80-km tunnel
- design of injector complex including e+ source, and polarized e- source
- machine detector interface, integration of accelerator ring at detector (s), low-beta quadrupoles, shielding (e.g. against beamstrahlung)?
- injection scheme
- polarization, Siberian snakes, spin matching, acceleration & storage, polarized sources

(19 September 2012)
TLEP

A design study of high-luminosity e^+e^- circular colliders for precise measurements of the properties of the Higgs-like H(126) boson and physics at the electroweak scale

(DRAFT)

Author list to be expanded and ordered by institute: R. Aleksan (CEA-Saclay), Alain Blondel (Geneva), John Ellis (King’s College London), Patrick Janot (CERN-PH), Mike Koratzinos (Geneva), Marco Zanetti (MIT), Frank Zimmermann (CERN-BE) … … …

Possible site layout and schematic for the TLEP collider

Abstract

We propose to carry out the design study of a high-energy, high-luminosity electron-positron storage ring collider operating in the energy range 90-350 GeV. Such a study was recommended as an outcome of the ICFA beam dynamics workshop on Higgs Factories and is in line with the proposed update of the European Strategy for Particle Physics. If situated in a 80km tunnel, this machine could be the precursor of a 80-100 TeV hadron collider as part of a possible long-term vision for CERN.
TLEP design study — preliminary structure for discussion

**Accelerator**
1. Optics, low beta, alignment and feedbacks
2. Beam beam interaction
3. Magnets and vacuum
4. RF system
5. Injector system
6. Integration w/(SHE)-LHC
7. Interaction region
8. Polarization & E-calib.
9. Elements of costing

**Experiments**
1. H(126) properties
2. Precision EW measurements at the Z peak and W threshold
3. Top quark physics
4. Experimental environment
5. Detector design
6. Online and offline computing

**Physics**
1. Theoretical implications and model building
2. Precision measurements, simulations and monte-carlos
3. Combination + complementarity with LHC and other machines; global fits

**Steering group**
- web site, mailing lists, speakers board, etc.

**Institutional board**

**International Advisory board**
summary

• **TLEP is a great opportunity for HEP!**
  – unparalleled “ZH” luminosity in 4 IPs, allowing for highest-precision Higgs studies
  – also Tera-Z and Mega-W factory, + t-tbar studies
  – future conversion into 100 TeV pp collider with lots of synergies (tunnel, cryo, detectors), & ep option

• LEP3 as backup

• **TLEP3 accelerator R&D to address key issues**
  – radiation shielding
  – IR optics, beam-beam effects, and injector ring
  – tunnel, RF system, arc magnets,…

• plans for **international collaboration & CDSR**
TLEP events & references


K. Oide, “SuperTRISTAN - A possibility of ring collider for Higgs factory,”
KEK Seminar, 13 February 2012

1st EuCARD LEP3 workshop, CERN, 18 June 2012
A. Blondel et al, “LEP3: A High Luminosity $e^+e^-$ Collider to study the Higgs Boson,”
arXiv:1208.0504, submitted to ESPG Krakow

P. Azzi et al, “Prospective Studies for LEP3 with the CMS Detector,”

2nd EuCARD LEP3 workshop, CERN, 23 October 2012

P. Janot, “A circular $e^+e^-$ collider to study H(125),” PH Seminar, CERN, 30 October 2012
ICFA Higgs Factory Workshop: Linear vs Circular, FNAL, 14-16 Nov. ’12


3rd TLEP3 Day, CERN, 10 January 2013

4th TLEP mini-workshop, CERN, 4-5 April 2013

https://espace.cern.ch/LEP3    https://cern.ch/accnet
“A circle is a round straight line with a hole in the middle.”

Mark Twain, in "English as She Is Taught", Century Magazine, May 1887
back-up slides
Circular HF HiTech option

Transmission-line HTS/LTS magnets

SC magnets require typically 10 x less space than NC magnet of the same field and gap; the magnet weight is very significantly reduced.

**HTS prototype dipole at FNAL**

Test: $B_{max} = 0.5\, T$, $I_{max} = 27\, kA$, $dB/dt_{max} = 10\, T/s$, $T_{max} \sim 25\, K$

Acceleration time $\sim 0.1\, s$, total cycle $\sim 1\, s$; fast SC magnets might support 1 minute lifetime in collider ring!
circular Higgs factories become popular around the world