Circular Higgs Factories & Possible Long-Term Strategy

Zimmermann, F (CERN)

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possible future circular colliders

• LHeC & SAPPHiRE
• HE-LHC or VHE-LHC
• LEP3 or TLEP
• even higher-energy $pp$ collider?
• ultimate limits
Large Hadron electron Collider (LHeC)

ERL LHeC:
recirculating linac with energy recovery
LHeC Conceptual Design Report

LHeC CDR published in


http://cern.ch/lhec

LHeC Study Group


About 150 Experimentalists and Theorists from 50 institutes

Thanks to all and to
CERN, ECFA, NuPECC

~600 pages
**L-R LHeC road map to $\geq 10^{33}$ cm$^{-2}$s$^{-1}$**

**luminosity of LR collider:**

(round beams)

$$L = \frac{1}{4\pi \epsilon} \frac{N_{b,p}}{\epsilon_p \beta_p^*}$$

- highest proton beam brightness “permitted” (ultimate LHC values)
  - $\gamma \epsilon = 3.75 \ \mu$m
  - $N_b = 1.7 \times 10^{11}$

- smallest conceivable proton $\beta^*$ function:
  - reduced $l^*$ (23 m $\to$ 10 m)
  - squeeze only one $p$ beam
  - new magnet technology $Nb_3Sn$

- $\beta_p^* = 0.1 \ m$

- average e$^-$ current limited by energy recovery efficiency
  - $I_e = 6.4 \ mA$

- maximize geometric overlap factor
  - head-on collision
  - small e$^-$ emittance
  - $\theta_c = 0$
  - $H_{hg} \geq 0.9$

- $H_D \approx 1.3$

D. Schulte
LHeC2010
LHeC ERL layout
two SC linacs, 3-pass up, 3-pass down; 6.4-mA 60-GeV e⁻’s collide w. LHC p/ions, e⁻ RF grad ~20 MV/m, 800 MHz

tune-up dump
10-GeV linac
comp. RF
injector

10-GeV linac
comp. RF
dump
IP
e⁻ final focus

total circumference ~ 8.9 km

(C=1/3 LHC allows for ion clearing gaps)

A. Bogacz, O. Brüning, M. Klein, D. Schulte, F. Zimmermann, et al
LHeC: 3 passes, flexible momentum compaction arc lattice building block: 52 m long cell with 2 (10) dipoles & 4 quadrupoles

LHeC flexible momentum compaction cell; tuned for small beam size (low energy) or low $\Delta \varepsilon$ (high energy)

Arc 1, Arc 2

Imaginary $\gamma_t$
Optics

$\langle H \rangle = 8.8 \times 10^{-3} \text{ m}$

limit chamber size
(>12 $\sigma$ at 25 mm diameter)

Arc 3, Arc 4

DBA-like Optics

$\langle H \rangle = 2.2 \times 10^{-3} \text{ m}$

Arc 5, Arc 6

TEM-like Optics

$\langle H \rangle = 1.2 \times 10^{-3} \text{ m}$

factor of 18 smaller than FODO

limit emittance growth

Alex Bogacz
prototype arc magnets

eRHIC dipole model (BNL)

5 mm gap
max. field 0.43 T (30 GeV)

LHeC dipole models (BINP & CERN)

25 mm gap
max. field 0.264 T (60 GeV)
LHeC test facility @ CERN

being designed by oPAC fellow Alessandra Valloni
### LHeC baseline & Higgs factory parameters

<table>
<thead>
<tr>
<th>parameter [unit]</th>
<th>LHeC baseline</th>
<th>LHeC Higgs factory</th>
</tr>
</thead>
<tbody>
<tr>
<td>species</td>
<td>$e^-$</td>
<td>$e^-$</td>
</tr>
<tr>
<td>beam energy (/nucleon) [GeV]</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>$25 (50)$</td>
<td>$25 (50)$</td>
</tr>
<tr>
<td>bunch intensity (nucleon) [$10^{10}$]</td>
<td>0.1 (0.2)</td>
<td>0.4 (0.8)</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>6.4</td>
<td>25.6</td>
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<tr>
<td>rms bunch length [mm]</td>
<td>0.6</td>
<td>0.6</td>
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<tr>
<td>polarization [%]</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>normalized rms emittance [$\mu$m]</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>geometric rms emittance [nm]</td>
<td>0.43</td>
<td>0.43</td>
</tr>
<tr>
<td>IP beta function $\beta_{x,y}$ [m]</td>
<td>0.12</td>
<td>0.039</td>
</tr>
<tr>
<td>IP spot size [$\mu$m]</td>
<td>7.2</td>
<td>4.1</td>
</tr>
<tr>
<td>synchrotron tune $Q_s$</td>
<td>—</td>
<td>$1.9 \times 10^{-3}$</td>
</tr>
<tr>
<td>hadron beam-beam parameter</td>
<td>0.0001 (0.0002)</td>
<td>0.0004 (0.0008)</td>
</tr>
<tr>
<td>lepton disruption parameter $D$</td>
<td>6</td>
<td>23 (31)</td>
</tr>
<tr>
<td>crossing angle</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>hourglass reduction factor $H_{hg}$</td>
<td>0.91</td>
<td>0.70 (0.73)</td>
</tr>
<tr>
<td>pinch enhancement factor $H_D$</td>
<td>1.35</td>
<td>1.35</td>
</tr>
<tr>
<td>c.m. energy [GeV]</td>
<td>1300</td>
<td>1300</td>
</tr>
<tr>
<td>luminosity / nucleon [$10^{33} \text{ cm}^{-2}\text{s}^{-1}$]</td>
<td>1.3</td>
<td></td>
</tr>
</tbody>
</table>

$L_{\text{ep}} \sim 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
a different type of collider

$s$-channel production;
lower energy;
no $e^+$ source

another advantage:
no beamstrahlung
$\rightarrow$ higher energy reach
than $e^+e^-$ colliders

$\gamma\gamma$ collider Higgs factory
\( \gamma \gamma \) collider based on \( e^- \)

Combining photon science & particle physics!

K.-J. Kim, A. Sessler
Beam Line
Spring/Summer 1996

Few \( J \) pulse energy with \( \lambda \sim 350 \text{ nm} \)
which beam & photon energy / wavelength?

\[ E_{\gamma,max} = \frac{x}{1 + x} E_{beam} \]

\[ x = \frac{4E_e \omega_L}{m_e^2} \cos^2 \frac{\theta}{2} \]

example \( x \approx 4.3 \)
(for \( x > 4.83 \) coherent pair production occurs)

with \( E_{beam} \approx 80 \text{ GeV} \): \( E_{\gamma,max} \approx 66 \text{ GeV} \)
\( E_{CM,max} \approx 132 \text{ GeV} \)

\( E_{photon} \approx 3.53 \text{ eV} \), \( \lambda \approx 351 \text{ nm} \)
SAPPHiRE: Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons

Reconfigured LHeC

total circumference ~ 9 km

scale ~ European XFEL, about 10-20k Higgs per year

10, 30, 50, 70 GeV for $e^\pm$ (8 arcs!)

500 MeV e- injector

11-GeV linac

dump
tune-up dump

$\gamma\gamma$ Higgs Factory

~0, 20, 40, 60 GeV for $e^\pm$ (8 arcs!)

IP

final focus
dump
tune-up dump

11-GeV linac

80 GeV

2.0 km
laser progress: example fiber lasers

power evolution of cw double-clad fiber lasers with diffraction limited beam quality over the past decade: factor 100 increase!

passive optical cavity

→

relaxed laser parameters

K. Moenig et al, DESY Zeuthen
laser options for SAPPHiRE

Cavity enhancement

\[ Q = 1000 \]

- 5 J, 10 MW circulating

SAPPHiRE laser

- Amplifier + Compressor
  - THG

LIFE beam line:
- Pulses at 16 Hz
- 8.125 kJ / pulse
- 130 kW average power
- ns pulse width

J. Gronberg, LLNL

Y. Zaouter, Amplitude Systems


G. Mourou, LOA;
M. Velasco,
Northwestern U.

Figure 2: Principle of a coherent amplifier network (CAN) based on fiber laser technology. An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of ~1 mJ at a high repetition rate (4). All the channels are combined coherently, compressed (5) and focused (6) to produce a pulse with an energy of >10 J at a repetition rate of 10 kHz (7). [3]
## LHeC Higgs factory comparison

(1 year = $10^7$ s at design luminosity).

<table>
<thead>
<tr>
<th>machine</th>
<th>LHeC</th>
<th>LHeC-HF</th>
<th>SAPPHiRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>luminosity</td>
<td>0.1 $(ep)$</td>
<td>2 $(ep)$</td>
<td>0.06 $(\gamma\gamma &gt; 125 \text{ GeV})$</td>
</tr>
<tr>
<td>$[10^{34} \text{ cm}^{-2}\text{s}^{-1}]$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cross section</td>
<td>$\sim 200 \text{ fb}$</td>
<td>$\sim 200 \text{ fb}$</td>
<td>$&gt;1.7 \text{ pb}$</td>
</tr>
<tr>
<td>no. Higgs/yr</td>
<td>2k</td>
<td>40k</td>
<td>$&gt;10k$</td>
</tr>
</tbody>
</table>
HFITT – HF in Tevatron tunnel

γγ collider inspired by SAPPHIRE

HFITT – Higgs Factory in Tevatron Tunnel

Goal: 10,000 Higgs/year

Tunnel Cross Section
(16 permanent magnet beam lines,
B = 0.05 – 3.3 kG)

RF (1.3 GHz, 8 sets, 5 cryomodules 1.25 GV /set)

E = 80 GeV
ρ = 800 m
U = 4.53 GeV/turn

I = 0.15 mA x 2
P(rf) = 27 MW

Weiren Chou, Gerard Mourou, Nikolay Solyak, Toshiki Tajima, Mayda Velasco, 20 May 2013
higher-energy $pp$ colliders
20-T dipole magnet

E. Todesco, L. Rossi, P. McIntyre
80-km tunnel for VHE-LHC – “best” option

even better 100 km?
## HE-LHC & VHE-LHC parameters – 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>HE-LHC</th>
<th>VHE-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>c.m. energy [TeV]</td>
<td>14</td>
<td>14</td>
<td>33</td>
<td>100</td>
</tr>
<tr>
<td>circumference $C$ [km]</td>
<td>26.7</td>
<td>26.7</td>
<td>26.7</td>
<td>80</td>
</tr>
<tr>
<td>dipole field [T]</td>
<td>8.33</td>
<td>8.33</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>dipole coil aperture [mm]</td>
<td>56</td>
<td>56</td>
<td>40</td>
<td>$\leq$ 40</td>
</tr>
<tr>
<td>beam half aperture [cm]</td>
<td>$\sim$ 2</td>
<td>$\sim$ 2</td>
<td>1.3</td>
<td>$\leq$ 1.3</td>
</tr>
<tr>
<td>injection energy [TeV]</td>
<td>0.45</td>
<td>0.45</td>
<td>$&gt;1.0$</td>
<td>$&gt;3.0$</td>
</tr>
<tr>
<td>no. of bunches $n_b$</td>
<td>2808</td>
<td>2808</td>
<td>2808</td>
<td>8420</td>
</tr>
<tr>
<td>bunch population $N_b$ [$10^{11}$]</td>
<td>1.15</td>
<td>2.2</td>
<td>0.94</td>
<td>0.97</td>
</tr>
<tr>
<td>init. transv. norm. emit. [µm]</td>
<td>3.75</td>
<td>2.5</td>
<td>1.38</td>
<td>2.15</td>
</tr>
<tr>
<td>initial longitudinal emit. [eVs]</td>
<td>2.5</td>
<td>2.5</td>
<td>3.8</td>
<td>13.5</td>
</tr>
<tr>
<td>no. IPs contributing to tune shift</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>max. total beam-beam tune shift</td>
<td>0.01</td>
<td>0.015</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>beam circulating current [A]</td>
<td>0.584</td>
<td>1.12</td>
<td>0.478</td>
<td>0.492</td>
</tr>
<tr>
<td>rms bunch length [cm]</td>
<td>7.55</td>
<td>7.55</td>
<td>7.55</td>
<td>7.55</td>
</tr>
<tr>
<td>IP beta function [m]</td>
<td>0.55</td>
<td>0.15 (min.)</td>
<td>0.35</td>
<td>1.1</td>
</tr>
<tr>
<td>rms IP spot size [µm]</td>
<td>16.7</td>
<td>7.1 (min.)</td>
<td>5.2</td>
<td>6.7</td>
</tr>
<tr>
<td>full crossing angle [µrad]</td>
<td>285</td>
<td>590</td>
<td>185</td>
<td>72</td>
</tr>
<tr>
<td>stored beam energy [MJ]</td>
<td>362</td>
<td>694</td>
<td>701</td>
<td>6610</td>
</tr>
</tbody>
</table>
HE-LHC & VHE-LHC luminosities could greatly improve for bunch spacings < 25 ns, e.g. by factor 5 for 5 ns, and make better use of strong radiation damping!

are 5 ns spacing & $2.5 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$ acceptable for detectors?

O. Dominguez, L. Rossi, F.Z.
**pp Higgs factories**

**LHC** is the 1st Higgs factory!  
\(E_{CM} = 8-14 \text{ TeV}, \hat{L} \sim 10^{34}\text{cm}^{-2}\text{s}^{-1}\)  
1 M Higgs produced so far – more to come!  
15 H bosons / min – and more to come

**HL-LHC** (~2022-2030):  
\(E_{CM} = 14 \text{ TeV}, L \sim 5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}\) (leveled)  
10x more Higgs

**HE-LHC**: in LHC tunnel (2035-?)  
\(E_{CM} = 33 \text{ TeV}, L = 5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}\)  
6x higher cross section for \(H\) self coupling

**VHE-LHC** in new 80-100 km tunnel (2040?)  
\(E_{CM} = 84-104 \text{ TeV}, L = 5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}\)  
42x higher cross section for \(H\) self coupling
circular $e^+e^-$
Higgs factories
circular $e^+e^-$ colliders to study the «Higgs boson» X(126)

a relatively young concept (2011)
proposed circular $e^+e^-$ Higgs factories

SuperTRISTAN in Tsukuba: 40 (& 60 or 80) km

SLAC/LBNL design: 27 km

Chinese Higgs Factory + Super $pp$ Collider

50 or 70 km

TLEP: 80 or 100 km near Geneva or HF in 27-km LHC tunnel (LEP3)

FNAL site filler, 16 km

FNAL Snowmass proposal: 100 km
circular $e^+e^-$ Higgs factories LEP3 & TLEP

**option 1:** installation in the LHC tunnel “LEP3”
- inexpensive  (only pay for new accelerator -- $\sim2B$ CHF)
- tunnel exists
- reusing ATLAS and CMS detectors
- reusing LHC cryoplants
- interference with LHC and HL-LHC

**option 2:** in new 80 or 100-km tunnel “TLEP”
- higher energy reach, 5-10x higher luminosity
- decoupled from LHC/HL-LHC operation & construction
- tunnel can later serve for VHE-LHC 100 TeV machine

**long term vision**
- more expensive because of tunnel
LEP3, TLEP

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

**Key Parameters**

<table>
<thead>
<tr>
<th></th>
<th>LEP3</th>
<th>TLEP</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/IP at 350 GeV c.m.</td>
<td>-</td>
<td>(1.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1})</td>
</tr>
<tr>
<td>Luminosity/IP at 240 GeV c.m.</td>
<td>(10^{34} \text{ cm}^{-2}\text{s}^{-1})</td>
<td>(4.8 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1})</td>
</tr>
<tr>
<td>Luminosity/IP at 160 GeV c.m.</td>
<td>(5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1})</td>
<td>(1.6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1})</td>
</tr>
<tr>
<td>Luminosity/IP at 90 GeV c.m.</td>
<td>(2 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1})</td>
<td>(5.6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1})</td>
</tr>
</tbody>
</table>

At the Z pole repeat the LEP physics programme in a few minutes...
<table>
<thead>
<tr>
<th></th>
<th>TLEP Z</th>
<th>TLEP W</th>
<th>TLEP H</th>
<th>TLEP t</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{beam}$ [GeV]</td>
<td>45</td>
<td>80</td>
<td>120</td>
<td>175</td>
</tr>
<tr>
<td>circumf. [km]</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>1180</td>
<td>124</td>
<td>24.3</td>
<td>5.4</td>
</tr>
<tr>
<td>#bunches/beam</td>
<td>4400</td>
<td>600</td>
<td>80</td>
<td>12</td>
</tr>
<tr>
<td>#e−/beam [10^{12}]</td>
<td>1960</td>
<td>200</td>
<td>40.8</td>
<td>9.0</td>
</tr>
<tr>
<td>horiz. emit. [nm]</td>
<td>30.8</td>
<td>9.4</td>
<td>9.4</td>
<td>10</td>
</tr>
<tr>
<td>vert. emit. [nm]</td>
<td>0.07</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>bending rad. [km]</td>
<td>9.0</td>
<td>9.0</td>
<td>9.0</td>
<td>9.0</td>
</tr>
<tr>
<td>$\kappa_{\varepsilon}$</td>
<td>440</td>
<td>470</td>
<td>470</td>
<td>1000</td>
</tr>
<tr>
<td>mom. c. $\alpha_{\varepsilon}$ [10^{-5}]</td>
<td>9.0</td>
<td>2.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$P_{loss,SR}$/beam [MW]</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
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<tr>
<td>$\beta^*_{x}$ [m]</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>$\beta^*_{y}$ [cm]</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$\sigma^*_{x}$ [$\mu$m]</td>
<td>124</td>
<td>78</td>
<td>68</td>
<td>100</td>
</tr>
<tr>
<td>$\sigma^*_{y}$ [$\mu$m]</td>
<td>0.27</td>
<td>0.14</td>
<td>0.14</td>
<td>0.10</td>
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</table>
## TLEP parameters – 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TLEP Z</th>
<th>TLEP W</th>
<th>TLEP H</th>
<th>TLEP t</th>
</tr>
</thead>
<tbody>
<tr>
<td>hourglass $F_{hg}$</td>
<td>0.71</td>
<td>0.75</td>
<td>0.75</td>
<td>0.65</td>
</tr>
<tr>
<td>$E_{SR,\text{loss/turn}}$ [GeV]</td>
<td>0.04</td>
<td>0.4</td>
<td>2.0</td>
<td>9.2</td>
</tr>
<tr>
<td>$V_{RF,\text{tot}}$ [GV]</td>
<td>2</td>
<td>2</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>$\delta_{max,RF}$ [%]</td>
<td>4.0</td>
<td>5.5</td>
<td>9.4</td>
<td>4.9</td>
</tr>
<tr>
<td>$\xi_x/IP$</td>
<td>0.07</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>$\xi_y/IP$</td>
<td>0.07</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>$f_s$ [kHz]</td>
<td>1.29</td>
<td>0.45</td>
<td>0.44</td>
<td>0.43</td>
</tr>
<tr>
<td>$E_{\text{acc}}$ [MV/m]</td>
<td>3</td>
<td>3</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>eff. RF length [m]</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>$f_{RF}$ [MHz]</td>
<td>700</td>
<td>700</td>
<td>700</td>
<td>700</td>
</tr>
<tr>
<td>$\delta_{SR,\text{rms}}$ [%]</td>
<td>0.06</td>
<td>0.10</td>
<td>0.15</td>
<td>0.22</td>
</tr>
<tr>
<td>$\sigma_{SR,z,\text{rms}}$ [cm]</td>
<td>0.19</td>
<td>0.22</td>
<td>0.17</td>
<td>0.25</td>
</tr>
<tr>
<td>$\mathcal{L}$/IP$[10^{32}\text{cm}^{-2}\text{s}^{-1}]$</td>
<td>5600</td>
<td>1600</td>
<td>480</td>
<td>130</td>
</tr>
<tr>
<td>number of IPs</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>beam lifet. [min]</td>
<td>67</td>
<td>25</td>
<td>16</td>
<td>20</td>
</tr>
</tbody>
</table>
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>
</tr>
</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>
</tr>
<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>
</tr>
<tr>
<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>

**TLEP has >10 times less SR heat load per meter than PEP-II or SPEAR!** (though higher photon energy)

N. Kurita, U. Wienands, SLAC
synchrotron radiation - activation

A. Fasso
3rd TLEP3 Day

see talk by A. Ferrari

Original LEP design

Fig. 2. Synchrotron Radiation Spectrum from LEP

$E = 130 \text{ GeV}$

$i = 1.0 \text{ mA}$

$R = 3544.5 \text{ m}$
beamstrahlung lifetime

- simulation w 360M macroparticles (guinea-pig)
- $\tau$ varies exponentially with momentum acceptance $\eta$

TLEP at 240 GeV post-collision
$E$ tail $\rightarrow$ lifetime $\tau$

M. Zanetti (MIT)

R-HF beamstrahlung more benign than for linear collider

luminosity $E$ spectrum

![Graph showing luminosity spectrum for different scenarios.](image-url)
beamstrahlung lifetime

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

beam lifetime versus acceptance $\delta_{\text{max}}$ for 4 IPs:

SuperKEKB: $\epsilon_y/\epsilon_x < 0.25\%$!
circular HFs - momentum acceptance

KEK design before optics correction ±1.1%

KEK design after optics correction ±1.3%

SLAC/LBNL design ±2.0%

FNAL site filler ±1.6%

T. Sen, E. Gianfelice-Wendt, Y. Alexahin
Next Collider: SuperKEKB

SuperKEKB is TLEP demonstrator!

$\beta_y^* = 300 \, \mu\text{m} \ (\text{TLEP}: \ 1 \, \text{mm})$

Lifetime 5 min (TLEP: $\sim$15 min)

$\varepsilon_y/\varepsilon_x = 0.25\% \ (\sim\text{TLEP})$

Off momentum acceptance

$e^+$ production rate

Beam commissioning will start early 2015
Luminosity Performance of $e^+e^-$ colliders

Circular colliders have several IP’s

- Lumi upgrade ($\times 3$) now envisioned at ILC: luminosity is key at low energy!
- Crossing point between circular and linear colliders $\sim 400$ GeV
- With fewer IP’s expect total luminosity of facility to scale approx as $(N_{IP})^{0.5}$
# Higgs factory performances

Precision on couplings, cross sections, mass, width, Summary of the ICFA HF2012 workshop (FNAL, Nov. 2012) arxiv1302:3318

The Circular Higgs Factory really goes to precision at few permil level.

## Table 2.1: Expected performance on the Higgs boson couplings from the LHC and $e^+e^-$ colliders, as compiled from the Higgs Factory 2012 workshop.

<table>
<thead>
<tr>
<th>Physical Quantity</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>ILC</th>
<th>Full ILC</th>
<th>CLIC</th>
<th>TLEP, 4 IP</th>
<th>TLEP, 4 IP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_H$</td>
<td>$1.7 \times 10^7$</td>
<td>$1.7 \times 10^8$</td>
<td>$6 \times 10^4 ZH$</td>
<td>$10^5 ZH$</td>
<td>$7.5 \times 10^4 ZH$</td>
<td>~$2 \times 10^5 ZH$</td>
<td>$2 \times 10^5 ZH$</td>
</tr>
<tr>
<td>$m_H$ (MeV)</td>
<td>100</td>
<td>50</td>
<td>35</td>
<td>35</td>
<td>100</td>
<td>26</td>
<td>7</td>
</tr>
<tr>
<td>$\Delta \Gamma_H$</td>
<td>10%</td>
<td>3%</td>
<td></td>
<td></td>
<td>ongoing</td>
<td>4%</td>
<td>1.3%</td>
</tr>
<tr>
<td>$\Delta \Gamma_{inv}/\Gamma_H$</td>
<td>Indirect (30%?)</td>
<td>Indirect (10%?)</td>
<td>Indirect (30%?)</td>
<td>Indirect (10%?)</td>
<td>Indirect (30%?)</td>
<td>Indirect (30%?)</td>
<td>Indirect (30%?)</td>
</tr>
<tr>
<td>$\Delta \theta_{H\gamma}/\theta_{H\gamma}$</td>
<td>6.5 – 5.1%</td>
<td>5.4 – 1.5%</td>
<td>--</td>
<td>--</td>
<td>ongoing</td>
<td>3.4%</td>
<td>1.4%</td>
</tr>
<tr>
<td>$\Delta \theta_{HH\gamma}/\theta_{HH\gamma}$</td>
<td>11 – 5.7%</td>
<td>7.5 – 2.7%</td>
<td>4.5%</td>
<td>2.5%</td>
<td>&lt; 3%</td>
<td>2.2%</td>
<td>0.7%</td>
</tr>
<tr>
<td>$\Delta \theta_{HHV}/\theta_{HHV}$</td>
<td>5.7 – 2.7%</td>
<td>4.5 – 1.0%</td>
<td>4.3%</td>
<td>1%</td>
<td>~1%</td>
<td>1.5%</td>
<td>0.25%</td>
</tr>
<tr>
<td>$\Delta \theta_{HHH}/\theta_{HHH}$</td>
<td>5.7 – 2.7%</td>
<td>4.5 – 1.0%</td>
<td>1.3%</td>
<td>1.5%</td>
<td>~1%</td>
<td>0.65%</td>
<td>0.2%</td>
</tr>
<tr>
<td>$\Delta \theta_{HH\gamma}/\theta_{HH\gamma}$</td>
<td>&lt; 30% (2 expts)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>~22% (~11% at 3 TeV)</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>$\Delta \theta_{HHH}/\theta_{HHH}$</td>
<td>&lt; 30%</td>
<td>&lt; 10%</td>
<td>--</td>
<td>--</td>
<td>10%</td>
<td>14%</td>
<td>7%</td>
</tr>
<tr>
<td>$\Delta \theta_{H\gamma\gamma}/\theta_{H\gamma\gamma}$</td>
<td>8.5 – 5.1%</td>
<td>5.4 – 2.0%</td>
<td>3.5%</td>
<td>2.5%</td>
<td>~3%</td>
<td>1.5%</td>
<td>0.4%</td>
</tr>
<tr>
<td>$\Delta \theta_{H\gamma\gamma}/\theta_{H\gamma\gamma}$</td>
<td>--</td>
<td>--</td>
<td>3.7%</td>
<td>2%</td>
<td>2%</td>
<td>2%</td>
<td>0.65%</td>
</tr>
<tr>
<td>$\Delta \theta_{H\gamma\gamma}/\theta_{H\gamma\gamma}$</td>
<td>15 – 6.9%</td>
<td>11 – 2.7%</td>
<td>1.4%</td>
<td>1%</td>
<td>1%</td>
<td>0.7%</td>
<td>0.22%</td>
</tr>
<tr>
<td>$\Delta \theta_{H\gamma\gamma}/\theta_{H\gamma\gamma}$</td>
<td>14 – 8.7%</td>
<td>8.0 – 3.9%</td>
<td>--</td>
<td>--</td>
<td>5%</td>
<td>3%</td>
<td>--</td>
</tr>
</tbody>
</table>

(*) The total luminosity is the sum of the integrated luminosity at each energy.
Need sub-percent precision for sensitivity to multi-TeV New Physics

- Compare (LHC), HL-LHC, ILC, TLEP

- TLEP reaches the needed sub-percent accuracy
- much theoretical work also needed
# TLEP TeraZ, Oku-W & Mega-Top

## Precision tests of EWSB

<table>
<thead>
<tr>
<th></th>
<th>LEP</th>
<th>ILC</th>
<th>TLEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s} \sim m_Z$</td>
<td>Mega-Z</td>
<td>Giga-Z</td>
<td>Tera-Z</td>
</tr>
<tr>
<td>#Z / year</td>
<td>2x10^7</td>
<td>Few 10^9</td>
<td>10^{12} (&gt;10^{11} b,c,\tau)</td>
</tr>
<tr>
<td>Polarization</td>
<td>Yes (T)</td>
<td>Easy</td>
<td>Yes (T,L)</td>
</tr>
<tr>
<td>Precision vs LEP1</td>
<td>1/5 to 1/10</td>
<td>~1/100</td>
<td>~1/100</td>
</tr>
<tr>
<td>Error on $m_Z$, $\Gamma_Z$</td>
<td>2 MeV</td>
<td>0.5 MeV</td>
<td>&lt; 0.1 MeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>LEP</th>
<th>ILC</th>
<th>TLEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s} = 240$ GeV</td>
<td>Oku-W</td>
<td></td>
<td></td>
</tr>
<tr>
<td># W pairs / 5 years</td>
<td>4x10^4</td>
<td>4x10^6</td>
<td>2x10^8</td>
</tr>
<tr>
<td>Polarization</td>
<td>No</td>
<td>Easy</td>
<td>Yes (T)</td>
</tr>
<tr>
<td>Error on $m_W$</td>
<td>33 MeV</td>
<td>3 MeV</td>
<td>0.5 MeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>LEP</th>
<th>ILC</th>
<th>TLEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s} \sim 350$ GeV</td>
<td></td>
<td></td>
<td>Mega-Top</td>
</tr>
<tr>
<td># top pairs / 5 years</td>
<td>-</td>
<td>100,000</td>
<td>500,000</td>
</tr>
</tbody>
</table>

- measure $m_Z$, $\Gamma_Z$ to < 0.1 MeV, $m_W$ to < 1 MeV, $\sin^2 \theta_W$ to $2.10^{-6}$ from $A_{LR}$
- TLEP beam polarization up to $W$ threshold, for energy calibration
other TLEP challenges

• **Efficient RF system**
  – Need 12 GeV/turn at 350 GeV
    • ~600 m of SC RF cavities @ 20 MV/m
      – LEP2 had 600 m at 7 MV/m
    – Very high power: up to 200 kW/cavity in collider ring
  • Power couplers similar to ESS –
    700-800 MHz preferred

• **Operation at the Z pole**
  – 4400 bunches: $e^+$ source, impedance effects, parasitic collisions
  • May need two rings designed to separate $e^+$ and $e^-$ beams
TLEP design study:  http://cern.ch/tlep

where you can subscribe for work, information, newsletter , etc...

Global endeavour: collaborators from Europe, US, Japan, China ,...

Next events: TLEP workshops 25-26 July 2013, Fermilab
16-18 October, CERN
Joint VHE-LHC+ TLEP kick-off meeting in February 2014
First 200 subscribers:

Distribution of countries of origin reflects the youth of the TLEP project and the very different levels of awareness in the different countries.

* * *

_distribution of countries_ 

A **iidience is remarkably well balanced between Accelerator, Experiment, and Phenomenology** -- the agreement with the three colour model is too good to be a statistical fluctuation!
VHE-LHC + TLEP

HE-LHC-LER (0.17→1.5 T)
TLEP collider (0.07 or 0.05T)
TLEP injector (0.007→0.05/7 T)

20 mm thick shield around cable
Gaps: 2 x V30xH60 mm

transmission line magnet
(B. Foster, H. Piekarz)

super-resistive cable

based on MgB$_2$ SC
only 12 MEuro/100 km!

HE-LHC (20 T)

Cable:
inner core of 40 mm Cu (700 mm$^2$)  
+ outer core : 2 layers, 150 strands of MgB$_2$, 1 kA each; Outer size 45 mm.  
120 kA =>120 k€/km !

For electrons: Cu water cooled,
$J_{\text{ov}}$ 2.5 A/mm$^2$

For protons: 800 A/strands  
120 kA (for >2.1 T); central copper acts as stabilizer

multipurpose tunnel
possible long-term strategy

(CERN implementation)

TLEP (80-100 km, $e^+e^-$, up to $\sim$350 GeV c.m.)

VHE-LHC ($pp$, up to 100 TeV c.m.)

& $e^\pm$ (120 GeV) – $p$ (7, 16 & 50 TeV) collisions ([V]HE-)TLHeC

≥50 years of $e^+e^-$, $pp$, $ep/A$ physics at highest energies

BUT - what if 100 TeV $pp$ collider is not enough ?!?
how to go beyond VHE-LHC?

the really grand challenge!
one possibility – crystal: world’s strongest magnets

\[ \lambda = 2\pi \beta = 2\pi \left( \frac{E}{\phi} \right)^{1/2} \]

straight crystal

\( \phi \approx 20-60 \text{ eV/Å}^2 \)

bent crystal

\( B_{\text{max}} \approx 2000 \text{ T}! \)

W. Scandale, MPL A (2012)

S.A. Bogacz, D. Cline, 1997
since 1978 crystals are used for extracting high-energy protons or ions from storage rings; can they also be used for a circular collider?!
channeling condition: angle of incidence < Lindhard critical angle \( \sim 5 \mu \text{rad} \) 

\( \frac{Z}{p} \left( \frac{\text{TeV}}{c} \right)^{1/2} \)

thermal vibrations, discreteness of lattice, electrons \( \rightarrow \) dechanneling (exponential decrease of channeled protons)

dechanneling length \( L_0 \sim 0.9 \text{ m } p[\text{TeV/c}] \)

cooling of crystal increases \( L_0 \)

minimum bending radius for channeling \( R_c \sim 0.4 \text{ m } p[\text{TeV/c}] \)
Nuclear loss rate seen by a scintillator telescope downstream of the crystal

Channeling peak

Reflection range

Amorphous orientation

x 5 reduction rate

Counts

Nuclear loss rate (including diffractive) strongly depressed

W. Scandale
profile of “beam” deflected by crystal

- 256×256 square pixels
- 1 pixel size = 55 µm
- 1 frame integration time 1 s
staging of crystal deflectors

6 strip crystals in series (each 2 mm long):
400 GeV/c protons reflected by 40±2 μrad
[effective field 16 T]
with efficiency 0.93±0.04

W. Scandale et al, Observation of Multiple Volume Reflection of Ultrarelativistic Protons by a Sequence of Several Bent Silicon Crystals, Phys.Rev.Lett. 102 (2009) 084801
possible longer-term strategy

(CERN implementation)

TLEP (80-100 km, \(e^+e^-,\) up to \(~350\) GeV c.m.)

VHE-LHC (\(pp,\) up to 100 TeV c.m.)

CCC, > 1 PeV

& \(e^\pm (120\) GeV) – \(p (7, 16 \& 50\) TeV\) collisions ([V)HE-]TLHeC)

\(\geq50\) years of \(e^+e^- , pp, ep/A\) physics at highest energies followed by >1 PeV circular crystal collider (CCC)!!?
circular crystal collider?

cryogenic? crystal bending stage

tunnel mostly empty

proton beam

a dream or our future?

energy ramp using induction acceleration?
highest-energy particles

4 July 2012 CERN, Geneva, Switzerland
Higgs boson – “God particle”? – mass $1.25 \times 10^{11}$ eV, neither matter nor force!

15 October 1991 Dugway Proving Ground, Utah, U.S.A.
“Oh-my-God-particle”!
(kinetic) energy $3 \times 10^{20}$ eV
($=3 \times 10^{11}$ GeV $= 300$ EeV)!
$10^{45} \text{ m}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}^{1.5}!$

cosmic-ray energy spectrum

P. Blasi, UHECR2012
The ultimate limit of electromagnetic acceleration is $E_{cr} \approx 10^{18} \text{ V/m}$, which is the critical field for $e^+e^-$ pair creation. The Planck scale of $10^{28} \text{ eV}$ would require a $10^{10} \text{ m}$ long accelerator, which is not an inconceivable task for an advanced technological society.

P. Chen, R. Noble, SLAC-PUB-7402, April 1998
summary

• proposed circular Higgs factories:
  LHeC (ep), SAPPHiRE (γγ) as intermediate HF’s & TLEP [or LEP3] as highest-luminosity e⁺e⁻
Higgs factory - staged: LHeC/SAPPHiRE concurrent with HL-LHC; TLEP after HL-LHC; note: LHeC/SAPPHiRE’s RF system identical to TLEP’s – can be recycled

• HL-LHC is developing technology (Nb₃Sn magnets, 20-kA HTS cables) for & TLEP shares tunnel with VHE-LHC pp collider (100 TeV c.m.); VHE-TLHeC

• coherent long-term strategy emerging, based on sharing, staging & synergies (high performance, minimum total cost)

• next next next machine: circular crystal collider?
possible long-term time line

- **LHC**
  - 1980: Design, R&D
  - 1990: Proto.
  - 2000: Constr.
  - 2010: Physics

- **HL-LHC**
  - Design, R&D
  - Constr.
  - Physics

- **LHeC/SAPPHiRE?**
  - Design, R&D
  - Constr.
  - Physics

- **TLEP**
  - Design, R&D
  - Constr.
  - Physics

- **VHE-LHC**
  - Design, R&D
  - Constr.
  - Physics

- **CCC**
  - Design, R&D
short LHC history

1983 *LEP Note 440* - S. Myers and W. Schnell propose twin-ring pp collider in LEP tunnel with 9-T dipoles

1991 CERN Council: LHC approval in principle
1992 EoI, Lol of experiments
1993 SSC termination
1994 CERN Council: LHC approval
1995-98 cooperation w. Japan, India, Russia, Canada, & US
2000 LEP completion
2006 last s.c. dipole delivered
2008 first beam
2010 first collisions at 3.5 TeV beam energy
2015 collisions at ~design energy (plan)

*we are already very late if we want to get a new machine by ~2040!*
oPAC help urgently needed!

• SAPPHiRE laser & optical cavity system
• IR designs for $\gamma\gamma$, $ep$, and $e^+e^-$ colliders
• highly efficient RF system for TLEP
• TLEP polarization up to 350 GeV?
• economical 20-T dipole
• $>100$-T magnets?
• efficient crystal channeling
• path to the Planck scale ($10^{16}$ TeV)?

thank you for your attention