Future High-Energy Frontier
Circular Colliders

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DESY Hamburg
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Work supported by the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453
outline

• [LHC &] HL-LHC \((pp)\)
• LHeC & SAPHiRE \((ep, \gamma\gamma)\)
• HE-LHC or VHE-LHC \((pp)\)
• LEP3 or TLEP \((e^+e^-)\)

• even higher-energy \(pp\) collider?
• alternative linear path
• ultimate limits
LHC: highest energy  \textit{pp}, AA, and \textit{pA} collider

design parameters

c.m. energy = 14 TeV ($p$)
luminosity = $10^{34}$ cm$^{-2}$s$^{-1}$

1.15x$10^{11}$ p/bunch
2808 bunches/beam

360 MJ/beam

$\gamma \varepsilon$=3.75 $\mu$m
$\beta^*$=0.55 m
$\theta_c$=285 $\mu$rad
$\sigma_z$=7.55 cm
$\sigma^*$=16.6$\mu$m
integrated $pp$ luminosity 2010-12

- **2010:** \(0.04 \text{ fb}^{-1}\)
  - 7 TeV CoM
  - Commissioning

- **2011:** \(6.1 \text{ fb}^{-1}\)
  - 7 TeV CoM
  - Exploring the limits

- **2012:** \(23.3 \text{ fb}^{-1}\)
  - 8 TeV CoM
  - Production

Data included from 2010-03-30 11:21 to 2012-12-16 20:49 UTC

M. Lamont, IPAC’13
reliable luminosity forecasts

2012 Measured vs Predicted

- Integrated Lumi 50 (pb-1)
- Measured 50ns (pb-1)
peak performance through the years

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy [TeV]</td>
<td>3.5</td>
<td>3.5</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>150</td>
<td>50</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>no. of bunches $n_b$</td>
<td>368</td>
<td>1380</td>
<td>1380</td>
<td>2808</td>
</tr>
<tr>
<td>$\beta^*$ [m] ATLAS and CMS</td>
<td>3.5</td>
<td>1.0</td>
<td>0.6</td>
<td>0.55</td>
</tr>
<tr>
<td>max. bunch intensity $N$ [protons/bunch]</td>
<td>$1.2 \times 10^{11}$</td>
<td>$1.45 \times 10^{11}$</td>
<td>$1.7 \times 10^{11}$</td>
<td>$1.15 \times 10^{11}$</td>
</tr>
<tr>
<td>normalized emittance $\gamma \varepsilon$ [mm-mrad]</td>
<td>$\sim 2.0$</td>
<td>$\sim 2.4$</td>
<td>$\sim 2.5$</td>
<td>3.75</td>
</tr>
<tr>
<td>peak luminosity $L$ [cm$^{-2}$s$^{-1}$]</td>
<td>$2.1 \times 10^{32}$</td>
<td>$3.7 \times 10^{33}$</td>
<td>$7.7 \times 10^{33}$</td>
<td>$1.0 \times 10^{34}$</td>
</tr>
</tbody>
</table>

>2x design when scaled to 7 TeV

M. Lamont, IPAC’13
Huge efforts over last months to prepare for high lumi and pile-up expected in 2012:

- optimized trigger and offline algorithms (tracking, calo noise treatment, physics objects)
  - mitigate impact of pile-up on CPU, rates, efficiency, identification, resolution
- despite x2 larger CPU/event and event size
  - we do not request additional computing resources (optimized computing model, increased fraction of fast simulation, etc.)

Z→μμ event from 2012 data with 25 reconstructed vertices

pile up will increase at higher energy → experiments request 25 ns operation in 2015
$\sqrt{s} = 7\, \text{TeV}$  \hspace{1cm} \int L dt = 0.05\, \text{fb}^{-1}  \hspace{1cm} \text{Apr 24, 2011}

**ATLAS Preliminary**

H$\to ZZ^{(*)}\to 4l$ channel

- **Signal** ($m_H = 125$ GeV)
- **Background ZZ(*)**
- **Background Z+jets, t\bar{t}**
- **Data**

**ATLAS & CMS**

$pp$ physics
The highlight of a remarkable year 2012
The Question of the next Decade(s)

What is really this Higgs boson that might have been discovered at ~ 125GeV?

"Higgs = emergency tire of the SM"

C. Grojean,
2nd LEP3/Tlep workshop,
18 June 2012

[picture courtesy to Andreas Weiler]
"Exploitation of the full potential of the LHC"

- LHC startup, $\sqrt{s} = 900$ GeV
- $\sqrt{s}=7\sim8$ TeV, $L=6\times10^{33}$ cm$^{-2}$ s$^{-1}$, bunch spacing 50 ns
- Go to design energy, nominal luminosity
- $\sqrt{s}=13\sim14$ TeV, $L\sim1.6\times10^{34}$ cm$^{-2}$ s$^{-1}$, bunch spacing 25 ns
- Injector and LHC Phase-1 upgrade to ultimate design luminosity
- $\sqrt{s}=14$ TeV, $L\sim2\times10^{34}$ cm$^{-2}$ s$^{-1}$, bunch spacing 25 ns
- HL-LHC Phase-2 upgrade, IR, crab cavities?
- $\sqrt{s}=14$ TeV, $L=5\times10^{34}$ cm$^{-2}$ s$^{-1}$, luminosity leveling

"Europe’s top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030."
Why High-Luminosity LHC? (LS3)

By continuous performance improvement and consolidation

Goal of HL-LHC project:
- 250 – 300 fb\(^{-1}\) per year
- 3000 fb\(^{-1}\) in about 10 years

By implementing HL-LHC

Around 300 fb\(^{-1}\) the present Inner Triplet magnets reach the end of their useful life (due to radiation damage) and must be replaced.

F. Bordry
The HL-LHC Project

Field progress in accelerator magnets

tesla
14
12
10
8
6
4
2
0

year
1975
1985
1995
2005
2015

Major intervention on more than 1.2 km of the LHC
Project leadership: L. Rossi and O. Brüning

New IR-quads Nb$_3$Sn (inner triplets)
New 11 T Nb$_3$Sn (short) dipoles
Collimation upgrade
Cryogenics upgrade
Crab Cavities
Cold powering
Machine protection

…
Large Hadron electron Collider (LHeC)

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

LHeC CDR published in
075001 (2012)

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
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

collide w. LHC $p$/ions, $e^-$ RF grad ~20 MV/m, 800 MHz

$\text{total circumference} \sim 8.9 \text{ km}$

(C=1/3 LHC allows for ion clearing gaps)
LHeC SRF & ERL test facility

design under study

CONFIGURATION 1 – 75 MeV PER PASS
FINAL ENERGY 150 MeV

CONFIGURATION 1 – 150 MeV PER PASS
FINAL ENERGY 300 MeV
(two additional arcs)

CONFIGURATION 1 – 300 MeV PER PASS
FINAL ENERGY 900 MeV

5 MeV Injector

Dump

various stages

A. Valloni, O. Brüning, E. Jensen, M. Klein
## LHeC baseline & Higgs factory parameters

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

$L_{ep} \sim 2 \times 10^{34}$ cm$^{-2}$s$^{-1}$
**γγ collider Higgs factory**

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

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few J pulse
energy with
λ~350 nm

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SAPPHiRE: Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons

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

total circumference ~ 9 km

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

Reconfigured LHeC

500 MeV e- injector

11-GeV linac

tune-up dump
laser options for SAPPHiRE

Y. Zaouter, Amplitude Systems

J. Gronberg, LLNL

EuCARD SAPPHiRE Day 19 February 2013

SAPPHiRE laser

Amplifier + Compressor

THG

Amplifier + Compressor

THG

Amplifier + Compressor

THG

Amplifier + Compressor

THG

Amplifier + Compressor

THG

Cavity enhancement

Q = 1000

5 J, 10 MW circulating

Livermore

LIFE Box in NIF Laser Bay

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

J. Gronberg, LLNL

full power w/o optical cavity!

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]


10 J at 10 kHz
## 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>$0.06\ (\gamma\gamma &gt;125\ GeV)$</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>$\sim200\ \text{fb}$</td>
<td>$\sim200\ \text{fb}$</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>
higher-energy $pp$ colliders
circular \textit{pp} Higgs factories

\textbf{LHC: 1st circular Higgs factory!} \\
$E_{\text{CM}} = 8-14 \text{ TeV}, \, \tilde{L} \sim 10^{34} \text{cm}^{-2}\text{s}^{-1}$ \\
1 M Higgs produced so far – more to come! \\
15 H bosons / min – and more to come

\textbf{HL-LHC: planned} (\textasciitilde 2022-2035): \\
$E_{\text{CM}} = 14 \text{ TeV}, \, L \sim 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ (leveled) \\
10x more Higgs

\textbf{HE-LHC: proposed} in LHC tunnel (2038-?) \\
$E_{\text{CM}} = 33 \text{ TeV}, \, L \geq 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ \\
6x higher cross section for $H$ self coupling

\textbf{or}

\textbf{VHE-LHC: proposed} in new 80-100 km tunnel (2040?) \\
$E_{\text{CM}} = 84-104 \text{ TeV}, \, L \geq 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ \\
42x higher cross section for $H$ self coupling

\textit{THE ultimate Higgs factory!}
High-Energy LHC

HE-LHC
20-T dipole magnets

S-SPS?

ALICE
ATLAS
CMS
LHC
LHCb
CNGS

higher energy transfer lines

2-GeV Booster

Linac4

n-ToF

AD
1999 (182 m)

PS
1959 (628 m)

1976 (7 km)

Gran Sasso
20-T dipole magnet

- HTS
- Nb$_3$Sn low $j$
- Nb$_3$Sn high $j$
- Nb$_3$Sn high $j$
- Nb-Ti

E. Todesco, L. Rossi, P. McIntyre
VHE-LHC

VHE-LHC-LER

SPS+, 1.3 TeV,
Main Parameters for VHE-LHC (FHC)

energy = 100 TeV c.m.
dipole field = 15 T (baseline) [20 T option] 
circumference ~100 km
#IPs = 2
total beam-beam tune shift = 0.01 
bunch spacing = 50 ns [5 ns option]
peak luminosity = 5x10^{34} \text{cm}^{-2}\text{s}^{-1}
\beta^* = 1.1 \text{ m} [2 \text{ m conservative option}]
linked to total beam current (~0.5-1 A)
<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>HE-LHC</th>
<th>FHC (50 ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c.m. energy [TeV]</td>
<td>14</td>
<td>33</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>circumference C [km]</td>
<td>26.7</td>
<td>26.7</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>dipole field [T]</td>
<td>8.33</td>
<td>20</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>dipole coil aperture [mm]</td>
<td>56</td>
<td>40</td>
<td>≤40</td>
<td></td>
</tr>
<tr>
<td>beam half aperture [cm]</td>
<td>~2</td>
<td>1.3</td>
<td>≤1.3</td>
<td></td>
</tr>
<tr>
<td>injection energy [TeV]</td>
<td>0.45</td>
<td>&gt;1.0</td>
<td>&gt;3.0?</td>
<td></td>
</tr>
<tr>
<td>No. of bunches</td>
<td>2808</td>
<td>2808</td>
<td>5265</td>
<td></td>
</tr>
<tr>
<td>Bunch population $N_b \times 10^{11}$</td>
<td>1.15</td>
<td>2.2</td>
<td>0.94</td>
<td>1.96</td>
</tr>
<tr>
<td>Init. tr. norm. emittance [μm]</td>
<td>3.75</td>
<td>2.5</td>
<td>1.38</td>
<td>4.28</td>
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<tr>
<td>Init. longit. emittance [eVs]</td>
<td>2.5</td>
<td>3.8</td>
<td>16.3</td>
<td></td>
</tr>
<tr>
<td>No. IPs contributing to $\Delta Q$</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Max. total b-b tune shift $\Delta Q$</td>
<td>0.01</td>
<td>0.015</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Beam current [A]</td>
<td>0.584</td>
<td>1.12</td>
<td><strong>0.478</strong></td>
<td><strong>0.495</strong></td>
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<tr>
<td>Rms bunch length [cm]</td>
<td>7.55</td>
<td>7.55</td>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td>IP beta function [m]</td>
<td>0.55</td>
<td>0.15</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>9.4</td>
</tr>
</tbody>
</table>
# HE-LHC & FHC parameters - 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>HE-LHC</th>
<th>FHC (50 ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full crossing angle [µrad]</td>
<td>285</td>
<td>590</td>
<td>185</td>
<td>102</td>
</tr>
<tr>
<td>Stored beam energy [MJ]</td>
<td>392</td>
<td>694</td>
<td>701</td>
<td>8264</td>
</tr>
<tr>
<td>SR power per ring [kW]</td>
<td>3.6</td>
<td>7.3</td>
<td>96.2</td>
<td>2130</td>
</tr>
<tr>
<td>Arc SR heat load [W/m/aperture]</td>
<td>0.17</td>
<td>0.33</td>
<td>4.35</td>
<td>25.7</td>
</tr>
<tr>
<td>Energy loss per turn [keV]</td>
<td></td>
<td>6.7</td>
<td>201</td>
<td>4300</td>
</tr>
<tr>
<td>Critical photon energy [eV]</td>
<td></td>
<td>44</td>
<td>575</td>
<td>4050</td>
</tr>
<tr>
<td>Photon flux [$10^{17}$/m/s]</td>
<td>1.0</td>
<td>2.0</td>
<td>1.9</td>
<td>1.2</td>
</tr>
<tr>
<td>Longit emittance damping time [h]</td>
<td></td>
<td>12.9</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Horiz. emittance damping time [h]</td>
<td></td>
<td>25.8</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Init. horiz. IBS ε rise time [h]</td>
<td>103</td>
<td>10.4</td>
<td>20</td>
<td>1886</td>
</tr>
<tr>
<td>Peak no. of events / crossing</td>
<td>27</td>
<td>135 (lev.)</td>
<td>147</td>
<td>342</td>
</tr>
<tr>
<td>Total/inel. cross section [mbarn]</td>
<td>111 / 85</td>
<td>129 / 93</td>
<td>153/108</td>
<td></td>
</tr>
<tr>
<td>Peak luminosity [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>1.0</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Beam lifetime due to burn off [h]</td>
<td>45</td>
<td>15.4</td>
<td>5.7</td>
<td>18.6</td>
</tr>
<tr>
<td>Optimum run time [h]</td>
<td>15.2</td>
<td>10.2</td>
<td>5.8</td>
<td>12.1</td>
</tr>
<tr>
<td>Opt. av. int. luminosity / day [fb$^{-1}$]</td>
<td>0.47</td>
<td>2.8</td>
<td>1.4</td>
<td>2.24</td>
</tr>
</tbody>
</table>
VHE-LHC: time evolution over 11 h in physics with $p$ burn off & controlled blow up

SR damping counteracted by transverse + longit. noise injection (constant tune shift & bunch length)

HE-LHC & VHE-LHC luminosities could greatly improve for bunch spacings $<$ 25 ns, e.g. by factor 5 for 5 ns, making better use of strong radiation damping!

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

HZ^0 W^- W^+ tt
circular $e^+e^-$ Higgs factories

• 2012 - LHC discovered Higgs boson at 126 GeV
• cross section for $H$ production in $e^+e^-$ collisions maximum at $\sim 15\%$ higher beam energy than LEP2
• circular collider (“TLEP”) in new 80-100 tunnel: 300x LEP2 luminosity at 4 IPs (precision $H$ studies)
• recipe for high luminosity: smaller $\beta^*$ (esp. $y$), lower emittance ($x$ & $y$), top-up injection
• operation up to $t\bar{t}$ threshold; very high luminosity at $Z$ pole & $WW$ threshold (+ polarized beams!)
• in same tunnel: $pp$ collider up to 100-TeV c.m. (VHE-LHC), and $ep$ collider
• TLEP will enhance VHE-LHC physics case
luminosity - past & planned $e^+e^-$ colliders

the circular route
TLEP beam lifetime: two limits

1. radiative Bhabha scattering \( (\sigma \approx 0.215 \text{ barn}) \)
   LEP2: \( \tau_{\text{beam,LEP2}} \sim 6 \text{ h} \)
   TLEP with \( L \sim 5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1} \) at 4 IPs:
   \( \tau_{\text{beam,TLEP}} \sim 21 \text{ minutes, unavoidable} \)

2. beamstrahlung (synchr. rad. during the collision) mitigated by:
   (1) large momentum acceptance \( \eta \)
   (2) flat beams [i.e. small \( \varepsilon_y \) & large \( \beta_x^* \)]
   (3) fast replenishing
   (M. Koratzinos, V.Telnov, K. Yokoya, M. Zanetti,...)
TLEP - circular $e^+e^-$ collider to study the «Higgs boson» X(126)

a relatively young concept (2011)

short beam lifetime ($\sim \tau_{\text{LEP2}}/40$) due to high luminosity
supported by top-up injection (used at KEKB, PEP-II, SLS,...)
top-up injection: schematic cycle

beam current in collider (15 min. beam lifetime)
- almost constant current

energy of accelerator ring
- 120 GeV
- 20 GeV

injection into collider

injection into accelerator

acceleration time = 1.6 s (assuming SPS ramp rate)
Top–up at KEKB (2004)

a day before top–up

- Top–up improved the integrated luminosity from 640 pb/day to 920 pb/day in 2004 (eventually reached 1480 pb/day in 2009).
- Machine becomes more stable and less aborts, as the stored beam current is nearly constant.
- Thus the luminosity tuning became easier.

K. Oide
top-up performance at PEP-II/BaBar

J. Seeman

Before Top-Up

After Top-Up

average luminosity ≈ peak luminosity
proposed circular $e^+e^-$ Higgs factories

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

SLAC/LBNL design: 27 km

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

Chinese Higgs Factory CEPC + Chinese $pp$ Collider

50 or 70 km

FNAL site filler, 16 km

FNAL Snowmass proposal: 100 km “TLEP”
Main Parameters for TLEP

energy = 91, 160, 240, 350 & 500 GeV c.m.
circumference ~100 km
total SR power ≤ 100 MW
#IPs = 2 or 4
beam-beam tune shift / IP scaled from LEP
peak luminosity / IP = 5x10^{34} cm^{-2}s^{-1} at the Higgs
top-up injection
$\beta_y^* = 1 \text{ mm} \sim \sigma_z$
<table>
<thead>
<tr>
<th>parameters</th>
<th>TLEP Z</th>
<th>TLEP W</th>
<th>TLEP H</th>
<th>TLEP t</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{c.m.}}$ [GeV]</td>
<td>91</td>
<td>160</td>
<td>240</td>
<td>350</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>1440</td>
<td>154</td>
<td>29.8</td>
<td>6.7</td>
</tr>
<tr>
<td># bunches/beam</td>
<td>7500</td>
<td>3200</td>
<td>167</td>
<td>160</td>
</tr>
<tr>
<td>#e- /bunch [$10^{11}$]</td>
<td>4.0</td>
<td>1.0</td>
<td>3.7</td>
<td>0.88</td>
</tr>
<tr>
<td>$\varepsilon_x$, $\varepsilon_y$ [nm]</td>
<td>29.2, 0.06</td>
<td>3.3, 0.017</td>
<td>7.5, 0.015</td>
<td>2, 0.002</td>
</tr>
<tr>
<td>$\beta_{x,y}$ [mm]</td>
<td>500, 1</td>
<td>200, 1</td>
<td>500, 1</td>
<td>1000, 1</td>
</tr>
<tr>
<td>$\sigma_{x,y}$ [$\mu$m]</td>
<td>121, 0.25</td>
<td>26, 0.13</td>
<td>61, 0.12</td>
<td>45, 0.045</td>
</tr>
<tr>
<td>$\sigma_{\text{tot}}_{z,rms}$ [mm] (w BS)</td>
<td>2.93</td>
<td>1.98</td>
<td>2.11</td>
<td>0.77</td>
</tr>
<tr>
<td>$E_{\text{SR}}$ loss/turn [GeV]</td>
<td>0.03</td>
<td>0.3</td>
<td>1.7</td>
<td>7.5</td>
</tr>
<tr>
<td>$V_{\text{RF}, \text{tot}}$ [GV]</td>
<td>2</td>
<td>2</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>$\xi_{x,y}/\text{IP}$</td>
<td>0.068</td>
<td>0.086</td>
<td>0.094</td>
<td>0.057</td>
</tr>
<tr>
<td>$\mathcal{L}$ /IP [$10^{34}$ cm$^{-2}$ s$^{-1}$]</td>
<td>59</td>
<td>16</td>
<td>5</td>
<td>1.3</td>
</tr>
<tr>
<td>#IPs</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>$\tau_{\text{beam}}$ [min] (rad.B)</td>
<td>99</td>
<td>38</td>
<td>24</td>
<td>21</td>
</tr>
<tr>
<td>$\tau_{\text{beam}}$ [min] (BS, $\eta=2%$)</td>
<td>$&gt;10^{25}$</td>
<td>$&gt;10^{6}$</td>
<td>9</td>
<td>3.5</td>
</tr>
<tr>
<td>parameters</td>
<td>LEP2</td>
<td>TLEP W</td>
<td>TLEP H</td>
<td>TLEP t</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td>$E_{c.m.}$ [GeV]</td>
<td>209</td>
<td>160</td>
<td>240</td>
<td>350</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>4</td>
<td>154</td>
<td>29.8</td>
<td>6.7</td>
</tr>
<tr>
<td># bunches/beam</td>
<td>4</td>
<td>3200</td>
<td>167</td>
<td>160</td>
</tr>
<tr>
<td>#e−/bunch [10^{11}]</td>
<td>5.8</td>
<td>1.0</td>
<td>3.7</td>
<td>0.88</td>
</tr>
<tr>
<td>$\varepsilon_x, \varepsilon_y$ [nm]</td>
<td>48, 0.25</td>
<td>3.3, 0.017</td>
<td>7.5, 0.015</td>
<td>2, 0.002</td>
</tr>
<tr>
<td>$\beta_{x,y}$ [mm]</td>
<td>1500, 50</td>
<td>200, 1</td>
<td>500, 1</td>
<td>1000, 1</td>
</tr>
<tr>
<td>$\sigma_{x,y}^*$ [\mu m]</td>
<td>270, 3.5</td>
<td>26, 0.13</td>
<td>61, 0.12</td>
<td>45, 0.045</td>
</tr>
<tr>
<td>$\sigma_{z,rms}^{tot}$ [mm] (w BS)</td>
<td>16.1</td>
<td>1.98</td>
<td>2.11</td>
<td>0.77</td>
</tr>
<tr>
<td>$E_{SR}^{loss}$/turn [GeV]</td>
<td>3.41</td>
<td>0.3</td>
<td>1.7</td>
<td>7.5</td>
</tr>
<tr>
<td>$V_{RF, tot}$ [GV]</td>
<td>3.64</td>
<td>2</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>$\xi_{x,y}/$IP</td>
<td>0.066 (y)</td>
<td>0.086</td>
<td>0.094</td>
<td>0.057</td>
</tr>
<tr>
<td>$\mathcal{L}$ /IP[10^{34}cm^{-2}s^{-1}]</td>
<td>0.0125</td>
<td>16</td>
<td>5</td>
<td>1.3</td>
</tr>
<tr>
<td>#IPs</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>$\tau_{beam}$ [min] (rad.B)</td>
<td>363</td>
<td>38</td>
<td>24</td>
<td>21</td>
</tr>
<tr>
<td>$\tau_{beam}$ [min] (BS, $\eta=2%$)</td>
<td>$&gt;10^{35}$</td>
<td>$&gt;10^6$</td>
<td>9</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Comparison with LEP2
<table>
<thead>
<tr>
<th>parameters</th>
<th>TLEP W</th>
<th>TLEP H</th>
<th>TLEP t</th>
<th>ZHH&amp;ttH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{c.m.}}$ [GeV]</td>
<td>160</td>
<td>240</td>
<td>350</td>
<td>500</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>154</td>
<td>29.8</td>
<td>6.7</td>
<td>1.6</td>
</tr>
<tr>
<td># bunches/beam</td>
<td>3200</td>
<td>167</td>
<td>160</td>
<td>20</td>
</tr>
<tr>
<td>#e−/bunch [10^{11}]</td>
<td>1.0</td>
<td>3.7</td>
<td>0.88</td>
<td>7.0</td>
</tr>
<tr>
<td>$\epsilon_x, \epsilon_y$ [nm]</td>
<td>3.3, 0.017</td>
<td>7.5, 0.015</td>
<td>2, 0.002</td>
<td>4., 0.004</td>
</tr>
<tr>
<td>$\beta_{x,y}$ [mm]</td>
<td>200, 1</td>
<td>500, 1</td>
<td>1000, 1</td>
<td>1000, 1</td>
</tr>
<tr>
<td>$\sigma_{x,y}$ [$\mu$m]</td>
<td>26, 0.13</td>
<td>61, 0.12</td>
<td>45, 0.045</td>
<td>126, 0.13</td>
</tr>
<tr>
<td>$\sigma_{z,\text{rms}}$ [mm] (w BS)</td>
<td>1.98</td>
<td>2.11</td>
<td>0.77</td>
<td>1.95</td>
</tr>
<tr>
<td>$E_{\text{SR}}$ loss/turn [GeV]</td>
<td>0.3</td>
<td>1.7</td>
<td>7.5</td>
<td>31.4</td>
</tr>
<tr>
<td>$V_{\text{RF, tot}}$ [GV]</td>
<td>2</td>
<td>6</td>
<td>12</td>
<td>35</td>
</tr>
<tr>
<td>$\xi_{x, y}$/IP</td>
<td>0.086</td>
<td>0.094</td>
<td>0.057</td>
<td>0.075</td>
</tr>
<tr>
<td>$\mathcal{L}$ /IP [10^{34}cm^{-2}s^{-1}]</td>
<td>16</td>
<td>5</td>
<td>1.3</td>
<td>1.0</td>
</tr>
<tr>
<td>#IPs</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>$\tau_{\text{beam}}$ [min] (rad.B)</td>
<td>38</td>
<td>24</td>
<td>21</td>
<td>26</td>
</tr>
<tr>
<td>$\tau_{\text{beam}}$ [min] (BS, $\eta=2%$)</td>
<td>$&gt;10^6$</td>
<td>9</td>
<td>3.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$\tau_{\text{beam}}$ [min] (BS, $\eta=3%$)</td>
<td>~1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
optics – TLEP arc cell

Y. Cai, B. Holzer, H. Burkhardt

ρ = 3100 m, \( L_{\text{cell}} = 79 \) m

ρ = 9100 m, \( L_{\text{cell}} = 50 \) m

\( \varepsilon_{x} = 48 \) nm at 104.5 GeV \( \rightarrow \) \( \varepsilon_{x} = 1.5 \) nm at 175 GeV

\( \varepsilon \propto \gamma^2 \theta^3 \): at lower beam energy increase cell length (“\( \theta \)” \( \times 2 \) or \( \times 6 \)!)
SuperKEKB – a TLEP demonstrator

beam commissioning will start in early 2015

- $\beta_y^*=300 \, \mu m$ (TLEP: 1 mm)
- lifetime 5 min (TLEP: ~15 min)
- $\varepsilon_y/\varepsilon_x=0.25\%$ ! (TLEP: 0.2\%)
- off momentum acceptance ($\pm1.5\%$, TLEP: $\pm2\%$)
- $e^+$ production rate ($2.5\times10^{12}/s$, TLEP: $<1\times10^{11}/s$)

\[ L = \frac{\gamma \pm \sqrt{\frac{\sigma_y^*}{\sigma_x^*}} I_{\pm \xi_{\pm y}}}{\beta_y^* \frac{R_L}{R_y}} \]
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 Z pole**
  – 7500 bunches: e⁺ source, impedance effects, parasitic collisions
  • *two separate rings for e⁺ and e⁻ beams will help here too*
polarization

**LEP**

observations + model predictions

**TLEP**

optimized scenario

> **100 keV beam energy calibration** by resonant depolarization (using pilot bunches) around Z peak and W pair threshold:

\[ \Delta m_Z \sim 0.1 \text{ MeV}, \quad \Delta \Gamma_Z \sim 0.1 \text{ MeV}, \quad \Delta m_W \sim 0.5 \text{ MeV} \]

A. Blondel

---

R. Assmann

**LEP**

loss of polarization due to growing energy spread

\[ \sigma_E \propto E^2 / \sqrt{\rho} \]

**TLEP**

\[ \rho = 9000 \text{ m}, \quad C = 80 \text{ km} \]

lower energy spread, high polarization up to W threshold

---

U Wienands, April 2013
e^+e^- Higgs factories: luminosity

ultimate precision at Z, WW, ZH; sensitive to New Physics in multi-TeV range & to SM closure → case for VHE-LHC

ultimate energy reach up to 1 or 3 TeV; direct searches for New Physics
## vertical rms IP spot sizes in nm

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<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>TLEP-H</strong></td>
<td><strong>120</strong></td>
</tr>
<tr>
<td>ATF2, FFTB</td>
<td>60 (35), 60 (40)</td>
</tr>
<tr>
<td><strong>SuperKEKB</strong></td>
<td><strong>50</strong></td>
</tr>
<tr>
<td>ILC</td>
<td>5 – 8</td>
</tr>
<tr>
<td>CLIC</td>
<td>1 – 2</td>
</tr>
</tbody>
</table>

In regular font: achieved

In italics: design values

$\beta_y^*$: 5 cm $\rightarrow$ 1 mm

TLEP will learn from ATF2 & SuperKEKB
# Higgs factory performances

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

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>LEP3, 4 IP</th>
<th>TLEP, 4 IP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>300 fb$^{-1}$/expt</td>
<td>3000 fb$^{-1}$/expt</td>
<td>250 GeV</td>
<td>250+350+1000 GeV</td>
<td>250 GeV (500 fb$^{-1}$)</td>
<td>240 GeV</td>
<td>240 GeV</td>
</tr>
<tr>
<td></td>
<td>5 yrs</td>
<td>5 yrs each</td>
<td>5 yrs</td>
<td>5 yrs each</td>
<td>5 yrs each</td>
<td>5 yrs each</td>
<td>5 yrs each</td>
</tr>
<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>$4 \times 10^5$ ZH</td>
<td>$2 \times 10^6$ 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>$\Delta \Gamma_H / \Gamma_H$</td>
<td>--</td>
<td>--</td>
<td>10%</td>
<td>3%</td>
<td>ongoing</td>
<td>4%</td>
<td>1.3%</td>
</tr>
<tr>
<td>$\Delta \Gamma_{\text{inv}} / \Gamma_H$</td>
<td>Indirect (30%?)</td>
<td>Indirect (10%?)</td>
<td>1.5%</td>
<td>1.0%</td>
<td>ongoing</td>
<td>0.35%</td>
<td>0.15%</td>
</tr>
<tr>
<td>$\Delta \rho_{3/2} / \rho_{3/2}$</td>
<td>6.5 - 5.1%</td>
<td>5.4 - 1.5%</td>
<td>--</td>
<td>5%</td>
<td>ongoing</td>
<td>3.4%</td>
<td>1.4%</td>
</tr>
<tr>
<td>$\Delta \rho_{1/2} / \rho_{1/2}$</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>$\Delta \rho_{3/2} / \rho_{3/2}$</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>$\Delta \rho_{1/2} / \rho_{1/2}$</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>$\Delta \rho_{HHT} / \rho_{HHT}$</td>
<td>--</td>
<td>&lt; 30% (2 expts)</td>
<td>--</td>
<td>~30% (~11% at 3 TeV)</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>$\Delta \rho_{HHH} / \rho_{HHH}$</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>$\Delta \rho_{HHT} / \rho_{HHT}$</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>$\Delta \rho_{HHT} / \rho_{HHT}$</td>
<td>--</td>
<td>--</td>
<td>3.7%</td>
<td>2%</td>
<td>2%</td>
<td>2.0%</td>
<td>0.65%</td>
</tr>
<tr>
<td>$\Delta \rho_{HHT} / \rho_{HHT}$</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>$\Delta \rho_{HHT} / \rho_{HHT}$</td>
<td>14 - 8.7%</td>
<td>8.0 - 3.9%</td>
<td>--</td>
<td>5%</td>
<td>3%</td>
<td>--</td>
<td>30%</td>
</tr>
</tbody>
</table>

(*) The total luminosity is the sum of the integrated luminosity at each energy.

**Circular Higgs Factory really goes to precision at few per mill level**
The case for a circular $e^+e^-$ Higgs factory

The discovery of a Higgs boson by the ATLAS and CMS collaborations at the LHC has opened new perspectives on accelerator-based particle physics. While much else might well be discovered at the LHC in its energy and luminosity increments, one item on the agenda of future accelerators is surely a Higgs factory capable of studying this new particle in as much detail as possible. Various options for such a facility are under active consideration and circular electron–positron ($e^+e^-$) colliders are amongst them.

In a real sense, a Higgs factory already exists in the form of the LHC, which has already produced millions of Higgs bosons and could produce hundreds of millions more with the high luminosity upgrade planned for the 2020s. However, the experimental conditions at the LHC restrict the range of Higgs decay modes that can be observed directly and measured accurately. For example, decays of the Higgs boson into charm quarks are unlikely to be measurable at the LHC. On the one hand, decays into gluons can be measured only indirectly via the rate of Higgs production by gluon–gluon annihilation and it will be difficult to quantify accurately invisible Higgs decays at the LHC. On the other hand, the large statistics at the LHC will enable accurate measurements of distinctive subdominant Higgs decays such as those into photon pairs or $ZZ$. The rare decay of the Higgs into liaison pairs will also be measurable. The task for a Higgs factory will be to make measurements that complement or are even more precise than those possible at the LHC.

**Attractive options**

Cleaner experimental conditions are offered by $e^+e^-$ collisions. Prominent among other contenders for a future Higgs factory are the International Linear Collider (ILC) and the Large Hadron Collider (LHC). In addition to running at the centre-of-mass energy of 240 GeV that is desirable for Higgs production, these also offer prospects for higher-energy collisions, e.g. at the top–antitop threshold of 350 GeV and at 500 GeV or 1000 GeV in the case of the LHC or even higher energies at CLIC. These would be some particularly attractive options if future, higher-energy LHC running reveals additional new physics within their reach. High-energy $e^+e^-$ collisions would also offer prospects for determining the triple-Higgs coupling, something that could be measured at the LHC only if it is operated at the highest possible luminosity.

There has recently been a resurgence of interest in the capabilities of circular $e^+e^-$ colliders being used as Higgs factories following a suggestion by Alan Blondel and Frank Zimmermann in December 2011 (Blondel and Zimmermann 2011). It is to be thought that the Large Electron–Positron (LEP) collider would be the largest and highest energy circular $e^+e^-$ collider and that linear colliders would be more cost-effective at higher energies. However, advances in accelerator technology since LEP was designed have challenged this view. In particular, the development of top-up injection at B factories and synchrotron radiation sources, as well as advances in superconducting RF and in beam-forming techniques at interaction points, raise the possibility of achieving collision rates at each interaction point at a circular Higgs factory that could be more than two orders of magnitude larger than those achieved at LEP. Moreover, it would be possible to operate such a collider with as many as four interaction points simultaneously as at LEP.

**There has been a resurgence of interest in circular $e^+e^-$ colliders being used as Higgs factories.**

The concept for a circular $e^+e^-$ collider that has been most studied at TEP would be installed in a tunnel some 200–200 km in circumference. This would be capable of collisions at 550 GeV in the centre of mass, while the specifications call for a luminosity of $10^{37} cm^{-2} s^{-1}$ at each interaction point. With the possible technical assumptions, the corresponding luminosity at a centre-of-mass energy of 240 GeV would exceed $4 \times 10^{35} cm^{-2} s^{-1}$ at each interaction point, as figure 1 (p.26) shows (Konstein et al. 2003). This encouraging at present circular $e^+e^-$ colliders – such as LEP2 and the B-factories – have established a track record of exceeding their design luminosities and that there are no obvious show-stoppers to achieving these targets at TEP.

The design luminosity of TEP would enable millions of Higgs bosons to be produced under clean experimental conditions. The Higgs mass could then be measured with a statistical precision below 10 GeV and the total decay width with an accuracy better than 1%. Many decay modes, such as those into quark pairs, WW, ZZ, and invisible decays could be measured with an accuracy better than 0.2% and gg decays to better than 1%. This would challenge the predictions of new low-supersymmetric models, which predict only small deviations of Higgs properties from those expected in the Standard Model, as figure 2 shows.

One essential limitation on the ambition for such a collider is the overall power consumption. The largest, single energy requirement is for the RF of a collider system. Fortunately, because it would operate in continuous rather than pulsed mode, experience with LEP suggests that an overall efficiency above 50% should be attainable. The collision performances quoted for LEP would require an RF power consumption of around 200 MW, to which should be added some 100 MW for cooling, ventilation, other services and the experiments. This is similar to the requirements of other major future accelerators at the energy frontier, such as the ILC and CLIC.

One attractive feature of circular $e^+e^-$ colliders is that they could offer significantly higher luminosities at lower energies. For example, a total luminosity of $2 \times 10^{35} cm^{-2} s^{-1}$ should be possible with TEP running at 8 and 5 GeV at the W and Z thresholds, which would offer prospects of data samples with millions of $10^6$ and $10^8$ events. The precision and the sensitivity of rare decays provided by such samples extend far beyond those envisaged in previous studies of Z and WW physics, corresponding, e.g., to $3 \times 10^6$ and $3 \times 10^7$ events at 5 and 8 GeV.

**Further reading**


Résumé

L’interprétation d’une unité à Higgs circulaire $e^+e^-$

La découverte d’un boson de Higgs au LHC a ouvert de nouvelles perspectives pour la physique des particules avec accélérateur. L’un des objets pourrait prendre forme d’un disque à Higgs, capable d’étudier la matière partielle aux énergies élevées. Plusieurs perspectives sont actuellement étudiées, notamment celle d’un accélérateur circulaire (le CERN). Dans cet article, John Ellis passe en revue les capacités d’une telle machine, en particulier l’utilité d’un accélérateur, qui serait installé dans un tunnel de 500 km de circonférence et pouvait produire des collisions à 550 GeV dans l’espace de masse.
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)

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

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

HE-LHC (20 T)

Super-resistive cable
based on MgB$_2$ SC
only 12 MEuro/100 km!

Multipurpose tunnel

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, $J_0$ 2.5 A/mm$^2$

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

Cryostat: 60 mm
He envelope: 50 mm
SC part: 2 layers MgB$_2$ (Bi2212) 150xØ1 mm
Cu inner core 40 mm
Cooling hole: 10 mm
common modular detectors for $e^+e^-$ and $pp$ collisions!

GMS-2T (TLEP)  GMS-4T (VHE-LHC)
VHE-LHC or FHLC / “Super-HERA”

Main Parameters

e- energy = 60, 120, 250 GeV

p energy = 50 TeV

IP spot size determined by p
e- current from FLC (SR power ≤ 50 MW)

#IPs = 1 or 2
<table>
<thead>
<tr>
<th>collider parameters</th>
<th>$e^\pm$ scenarios</th>
<th>protons</th>
</tr>
</thead>
<tbody>
<tr>
<td>species</td>
<td>$e^\pm$</td>
<td>$e^\pm$</td>
</tr>
<tr>
<td>beam energy [GeV]</td>
<td>60</td>
<td>120</td>
</tr>
<tr>
<td>bunch spacing [µs]</td>
<td>0.125</td>
<td>2</td>
</tr>
<tr>
<td>bunch intensity [$10^{11}$]</td>
<td>3.8</td>
<td>3.7</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>477</td>
<td>29.8</td>
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<tr>
<td>rms bunch length [cm]</td>
<td>0.25</td>
<td>0.21</td>
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<tr>
<td>rms emittance [nm]</td>
<td>6.0, 3.0</td>
<td>7.5, 3.75</td>
</tr>
<tr>
<td>$\beta_{x,y}$ *[mm]</td>
<td>5.0, 2.5</td>
<td>4.0, 2.0</td>
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<tr>
<td>$\sigma_{x,y}$ *[µm]</td>
<td></td>
<td></td>
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<tr>
<td>b-b parameter $\xi$</td>
<td>0.13</td>
<td>0.050</td>
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<tr>
<td>hourglass reduction</td>
<td>0.42</td>
<td>0.36</td>
</tr>
<tr>
<td>CM energy [TeV]</td>
<td>3.5</td>
<td>4.9</td>
</tr>
<tr>
<td>luminosity [10^{34}cm^{-2}s^{-1}]</td>
<td>21</td>
<td>1.2</td>
</tr>
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</table>
FCC - 80-100 km tunnel infrastructure in Geneva area – design driven by $pp$-collider requirements with possibility of $e^+e^-$ (TLEP) and $p-e$ (VLHeC)

FCC (Future Circular Colliders)
CDR and cost review for the next ESU (2018) (including injectors)

$15 \text{T} \Rightarrow 100 \text{ TeV in 100 km}
20 \text{T} \Rightarrow 100 \text{ TeV in 80 km}$
### FCC Study Scope and Structure


<table>
<thead>
<tr>
<th>Infrastructure</th>
</tr>
</thead>
<tbody>
<tr>
<td>tunnels, surface buildings, transport (access roads), civil engineering, cooling ventilation, electricity, cryogenics, communication &amp; IT, fabrication and installation processes, maintenance, environmental impact and monitoring,</td>
</tr>
</tbody>
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<tr>
<th>Hadron injectors</th>
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<tr>
<td>Detector concept</td>
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<td>Physics requirements</td>
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<td>Operation concept</td>
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<tr>
<td>Detector concept</td>
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<td>Physics requirements</td>
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<th>e- p option:</th>
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<tr>
<td>Physics, Integration, additional requirements</td>
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**FCC Study Scope and Structure**

**Hadron injectors**
- Beam optics and dynamics
- Functional specs
- Performance specs
- Critical technical systems
- Operation concept

**Hadron collider**
- Optics and beam dynamics
- Functional specifications
- Performance specs
- Critical technical systems
- Related R+D programs
- *HE-LHC comparison*
- Operation concept
- Detector concept
- Physics requirements

**e+ e- collider**
- Optics and beam dynamics
- Functional specifications
- Performance specs
- Critical technical systems
- Related R+D programs
- Injector (Booster)
- Operation concept
- Detector concept
- Physics requirements

**e- p option:** Physics, Integration, additional requirements
FCC Design Study Leaders

Michael Benedikt
Leader

Frank Zimmermann
Deputy Leader
Main areas for design study

Machines and infrastructure conceptual designs
- Infrastructure
- Hadron collider conceptual design
- Hadron injectors
- Lepton collider conceptual design
- Safety, operation, energy management environmental aspects

Technologies R&D activities Planning
- High-field magnets
- Superconducting RF systems
- Cryogenics
- Specific technologies
- Planning

Physics experiments detectors
- Hadron physics experiments interface, integration
- $e^+ e^-$ coll. physics experiments interface, integration
- $e^-$ - p physics and integration aspects

Preparatory group for a kick-off meeting => Steering committee

F. Bordry
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)

$\geq 50$ years of $e^+e^-$, $pp$, $ep/A$ physics at highest energies
intermediate conclusions

• LHC running well & predictably; HL-LHC develops the technology ($Nb_3Sn$ magnets, 20-kA HTS cables) for future higher energy $pp$ collider: HE-LHC (33 TeV c.m.) and/or VHE-LHC (100 TeV c.m.)

• TLEP, in VHE-LHC tunnel, being studied as highest-luminosity $e^+e^-$ Higgs factory
  - excellent energy resolution, & superb performance at $Z$ pole, $W$ & top threshold

• coherent long-term strategy emerging, based on sharing, staging & synergies (high performance, minimum total cost, maximum energy reach)
possible long-term time line

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

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

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

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

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

- **VHE-LHC**
  - Design, R&D
  - Constr.
  - Physics
how to go beyond VHE-LHC?
one possibility –
crystal: world’s strongest magnets

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

\[ \phi \sim 20-60 \text{ eV/Å}^2 \]

\[ B_{\text{max}} \approx 2000 \text{ T}! \]

W. Scandale, MPL A (2012)

S.A. Bogacz, D. Cline, 1997
crystal extraction from stored proton/ion beam

since 1978 crystals are used for extracting high-energy protons or ions from storage rings; can they also be used for a circular collider?!
Nuclear loss rate seen by a scintillator telescope downstream of the crystal strongly depressed

*Nuclear loss rate (including diffractive) strongly depressed*
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

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

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

schematic layout of the experimental setup used to study multiple volume reflection at the H8 beam line of the CERN SPS
circular long-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)

\(\geq\)50 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?

cryogenic (?) crystal bending stage

energy ramp using induction acceleration?
linear long-term strategy

ILC
500 GeV
SC 1.3 GHz
klystrons
31.5 MV/m
31 km

e^+e^- collisions up 10 TeV c.m.

ILC
1 TeV
SC 1.3 GHz
klystrons
45 MV/m?
41 km

CLIC
3 TeV
drive beam
NC 12 GHz
100 MV/m
48 km

DWAC
10 TeV
drive beam
D 26 GHz
270 MV/m
48 km

XRCMC
1000 TeV,
drive beam for
X-ray lasers,
crystal
27 GV/m
48 km

1 PeV µ^+µ^- collisions
$e^\pm$ may soon run out of steam in the high-gradient world! ($E_{\text{max}} \sim 300 \text{ GeV}?$)

→ need to change particle type

**linear X-ray crystal \(\mu\) collider**

**issues:**
- \(\mu\) production rate
- neutrino radiation

Vladimir Shiltsev, 2012
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)!
LHC $\rho$ energy

$10^{45}$ m$^{-2}$ s$^{-1}$ sr$^{-1}$ GeV$^{1.5}$

HE-LHC

VHE-LHC

circular crystal collider

cosmic-ray energy spectrum
circular roadmap

$E^{2.5} J(E) (m^{-2} s^{-1} sr^{-1} GeV^{1.5})$

GZK limit

P. Blasi,
UHECR2012

$1 \times 10^8$

$\times 10^8$
$10^{45} \text{ m}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{1.5}$!

cosmic-ray energy spectrum

linear roadmap

metal linear colliders

dielectric & plasmas

crystal accelerator driven by X-ray laser

P. Blasi, UHECR2012

GZK limit

LHC $p$ energy

$x10^8$
ultimate limit
of electromagnetic acceleration

\[ E_{\text{cr}} \approx 10^{18} \text{ V/m} \]

critical field for \( e^+e^- \) pair creation - \( \frac{\hbar}{(m_e c)} e E_{\text{cr}} \sim m_e c^2 \)

reaching Planck scale of \( 10^{28} \text{ eV} \)

would need \( 10^{10} \text{ m} \) long accelerator

[\( 10^{10} \text{ m} = 1/10\text{th of distance earth-sun} \)]

“not an inconceivable task for an advanced technological society”

P. Chen, R. Noble, SLAC-PUB-7402, April 1998
ultimate limit of electromagnetic bending

\( B_{cr} \approx 4 \times 10^9 \) T critical field for \( e^+e^- \) pair creation - \( B_{cr} \sim E_{cr} / c \)

reaching Planck scale of \( 10^{28} \) eV would need \( \sim 10^{10} \) m wide storage ring
\([10^{10} \text{ m} = 1/10\text{th of distance earth-sun}]\)

linear & circular Planck-scale colliders have comparable size
long-term conclusions
bright future for accelerator-based HEP!
• many new technologies emerging
several routes to 10-TeV/100-TeV & 1 PeV collisions
e.g. linear path: ILC → CLIC → DWAC → XRCMC
circular path: LHC/HL-LHC → LHeC? →
   → TLEP → VHE-LHC → CCC
crystals may be key for both bending and/or acceleration
eventually outer-space solar-system accelerator needed to reach Planck mass
possible long-term time line


LHC
- Design, R&D
- Proto.
- Constr.
- 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
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, LoI 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!

>30 years!
“Of course, it should not be the size of an accelerator, but its costs which must be minimized.”

Gustav-Adolf Voss, 1995