Circular Higgs Factories: LEP3, TLEP and SAPPHiRE

Frank Zimmermann
J.A.I., Oxford, 1 November 2012

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4 July 2012 - X(125) “Higgs” discovery
Part 1 – LEP3 / TLEP
Higgs $e^+e^-$ production cross section

Figure 5: The Higgs boson production cross section as a function of the centre-of-mass energy. The red curve corresponds to the Higgsstrahlung process only, $e^+e^- \rightarrow HZ$, and the blue curve includes the WW and ZZ fusion processes as well, together with their interference with the Higgsstrahlung process. The right graph is a zoom of the left graph around the maximum of the cross section.

Prospective Studies for LEP3 with the CMS Detector

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2 Massachusetts Institute of Technology
3 INFN, Sezione di Padova

best for tagged ZH physics:
$E_{cm} = m_H + 111^{\pm 10}$
W. Lohmann et al. LCWS/ILC2007

take 240 GeV
Higgs production mechanism

in $e^+e^-$ collisions a light Higgs is produced by the “Higgstrahlung” process close to threshold; production section has a maximum at near threshold $\sim 200$ fb

$10^{34}/\text{cm}^2/\text{s} \Rightarrow 20'000$ $H$-$Z$ events per year.

For a Higgs of 125GeV, a centre of mass energy of 240GeV is sufficient $\Rightarrow$ kinematical constraint near threshold for high precision in mass, width, selection purity.

A. Blondel
**Z - tagging by missing mass**

**Graph and Diagrams:**

1. **Graph 1:**
   - **Title:** $ZH \rightarrow \mu^+ \mu^- X$ (ILC)
   - **Axes:**
     - X-axis: $M_{recoil}$ (GeV)
     - Y-axis: Events / (0.2)
   - **Data Points:**
     - Sig + Bkg
     - Sig
     - Fit to Sig + Bkg
     - Fit to Bkg

2. **Diagram 1:**
   - **Diagram Description:**
     - $e^-$
     - $H$
     - $Z^*$
     - $e^+$
   - **Equation:**
     - Total rate $\propto g_{HZZ}^2$
     - $ZZZ$ final state $\propto g_{HZZ}^4 / \Gamma_H$
   - **Measure:**
     - $\Gamma_H$

3. **Graph 2:**
   - **Title:** Z -> ll with H -> anything
   - **Legend:**
     - Signal
     - All backgrounds
     - WW
     - Zvv, Zee, Wev
     - Hll
   - **X-axis:** Higgs mass (GeV)
   - **Y-axis:** Events / 2 GeV

**Overall Context:**

The document discusses the tagging of $Z$ by missing mass and the total rate and width of the Higgs boson in the $ZZZ$ final state. The diagrams and graphs illustrate the experimental and theoretical aspects of this process, focusing on the decay of $Z$ and the interaction with the Higgs boson to produce a final state with a specific signature.
possible future projects at CERN

- PSB PS (0.6 km)
- SPS (6.9 km)
- LHC (26.7 km)

- TLEP (80 km, \( e^+e^- \), up to \(~400\) GeV c.m.)
- LEP3 (240 GeV c.m.)
- VHE-LHC (\( pp \), up to 100 TeV c.m.)

also: \( e^\pm (200\) GeV) – \( p (7 \& 50\) TeV) collisions
two options

• installation in the LHC tunnel “LEP3”
  + inexpensive (<0.1xLC)
  + tunnel exists
  + reusing ATLAS and CMS detectors
  + reusing LHC cryoplants
  - interference with LHC and HL-LHC

• new larger tunnel “DLEP” or “TLEP”
  + higher energy reach, 5-10x higher luminosity
  + decoupled from LHC and HL-LHC operation and construction
  + tunnel can later serve for HE-LHC (factor 2-3 in energy from tunnel alone) with LHC remaining as injector
  - 3-4x more expensive (new tunnel, cryoplants, detectors?)
**LEP3**

\[(e^+e^- \rightarrow ZH, \ e^+e^- \rightarrow W^+W^-, \ e^+e^- \rightarrow Z)\]

**key parameters**

circumference: 26.7 km (LHC tunnel)

maximum beam energy: \(\geq 120\ \text{GeV}\)

luminosity in each of 2-4 experiments:

\[\geq 10^{34}\ \text{cm}^{-2}\text{s}^{-1} \text{ at ‘Higgs energy’ (} \sim 240\ \text{GeV c.m.)}\]

\[\geq 5\times10^{34}\ \text{cm}^{-2}\text{s}^{-1} \text{ at } 2\times M_W \text{ (} \sim 160\ \text{GeV c.m.)}\]

\[\geq 2\times10^{35}\ \text{cm}^{-2}\text{s}^{-1} \text{ at the Z pole (} \sim 90\ \text{GeV c.m.)}\]
LEP3 key parameters

arc optics
• same as for LHeC: $\varepsilon_{x,LHeC} < 1/3 \varepsilon_{x,LEP1.5}$ at equal beam energy,
• optical structure compatible with present LHC machine
• small momentum compaction (short bunch length)
• assume $\varepsilon_y/\varepsilon_x \sim 5 \times 10^{-3}$ similar to LEP (ultimate limit $\varepsilon_y \sim 1$ fm from opening angle)

RF
• RF frequency 1.3 GHz or 700 MHz
• ILC/ESS-type RF cavities high gradient (20 MV/m assumed, 2.5 times LEP gradient)
• total RF length for LEP3 at 120 GeV similar to LEP at 104.5 GeV
• short bunch length (small $\beta_y^*$)
• cryo power $<1/2$ LHC

synchrotron radiation
• energy loss / turn: $E_{\text{loss}}[\text{GeV}] = 88.5 \times 10^{-6} (E_b[\text{GeV}])^4 / \rho[\text{m}]$.
• higher energy loss than necessary
• arc dipole field = 0.153 T
• compact magnet
• critical photon energy = 1.4 MeV
• 50 MW per beam (total wall plug power $\sim 200$ MW $\sim$ LHC complex) $\rightarrow 4 \times 10^{12}$ $e^\pm$/beam
putting LEP3 into the LHC tunnel?

LHC tunnel cross section with space reserved for a future lepton machine like LEP3 [blue box above the LHC magnet] and with the presently proposed location of the LHeC ring [red]
integrating LEP3 IR in CMS detector?

Azzi, et al.

QUADS insertions in the CMS detector

A. Blondel, ATLAS Meeting 4 Oct. 2012
integrating LEP3 IR in ATLAS detector?

Based on M. Nessi
CARE-HHH IR’07

Particle rates in Hz/cm²

RPC OUTER:

RPC MID:

MDT IN:

LW MDT

BW MDT

n₁: neutrons E < 0.1 MeV
n₂: neutrons 0.1 < E < 10 MeV
n₃: neutrons E > 10 MeV
γ: photons
e: electrons E > 0.01 MeV
μ: muons E > 10 MeV
p: protons E > 10 MeV
π: pions E > 10 MeV

- z = 3.49-4.58 m
  rₘₐₓ = 18 cm
- z = 6.8-8.66 m
  rₘₐₓ = 43 cm
- z = 8.69-12.87 m
  rₘₐₓ = 87 cm
- z = 12.95-18.60 m
  rₘₐₓ = 150 cm

Based on M. Nessi CARE-HHH IR’07
TLEP

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

key parameters

circumference: \(\sim 80\) km (3x LHC)

maximum beam energy: \(\geq 175\) GeV

luminosity in each of 2-4 experiments:

\(\sim 10^{34}\) cm\(^{-2}\)s\(^{-1}\) at \(t\bar{t}\) threshold (\(\sim 350\) GeV c.m.)

\(\geq 5 \times 10^{34}\) cm\(^{-2}\)s\(^{-1}\) at ‘Higgs energy’ (\(\sim 240\) GeV c.m.)

\(\geq 1.5 \times 10^{35}\) cm\(^{-2}\)s\(^{-1}\) at \(2\times M_W\) (\(\sim 160\) GeV c.m.)

\(\geq 10^{36}\) cm\(^{-2}\)s\(^{-1}\) at the Z pole (\(\sim 90\) GeV c.m.)
a new tunnel for TLEP in the Geneva area?
TLEP tunnel in the Geneva area – “best” option

«Pre-Feasibility Study for an 80-km tunnel at CERN»
John Osborne and Caroline Waaijer,
CERN, ARUP & GADZ, submitted to ESPG
SuperTRISTAN in Tsukuba: 40–80 km ring

Proposal by K. Oide, 13 February 2012

TLEP tunnel in the KEK area?

12.3 km
luminosity formulae & constraints

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

\[ (f_{rev} n_b N_b) = \frac{P_{SR, \rho}}{8.8575 \times 10^{-5} \frac{m}{GeV^{-3}} E^4} \]

SR radiation power limit

\[ \frac{N_b}{\varepsilon_x} = \frac{\xi x 2\pi y (1 + \kappa_\sigma)}{r_e} \]

beam-beam limit

\[ \frac{N_b}{\sigma_x \sigma_z} \frac{30 \gamma r_e^2}{\delta_{acc} \alpha} < 1 \]

>30 min beamstrahlung lifetime (Telnov) \( \rightarrow N_b, \beta_x \)
optimum LEP3/TLEP luminosity

minimizing

\[ \kappa_\varepsilon = \varepsilon_y / \varepsilon_x \]

\[ \beta_y \sim \beta_x (\varepsilon_y / \varepsilon_x) \quad [\text{so that } \xi_x = \xi_y] \]

increases the luminosity independently of previous limits

respect \( \beta_y \geq \sigma_z \) (hourglass effect)
<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>
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<td>beam energy $E_b$ [GeV]</td>
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<td>120</td>
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<tr>
<td>Parameter</td>
<td>LEP2</td>
<td>LHeC</td>
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<td>$V_{RF,tot}$ [GV]</td>
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<td>$\xi_x$/IP</td>
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<td>0.12</td>
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<td>0.12</td>
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<td>42</td>
<td>600</td>
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<td>600</td>
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<td>700</td>
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<td>0.12</td>
<td>0.23</td>
<td>0.06</td>
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<td>$\sigma_{SR,z,rms}$ [cm]</td>
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<td>0.69</td>
<td>0.31</td>
<td>0.19</td>
<td>0.17</td>
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<td>$L/IP[10^{32}cm^{-2}s^{-1}]$</td>
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<td>N/A</td>
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<td>10335</td>
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<td>65</td>
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<td>2</td>
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<td>0.05</td>
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<td>4</td>
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<td>$n_\gamma/collision$</td>
<td>0.08</td>
<td>0.16</td>
<td>0.60</td>
<td>0.41</td>
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<td>$\Delta \delta_{BS}/collision$ [MeV]</td>
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<td>0.02</td>
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<td>$\Delta \delta_{BS,rms}/collision$ [MeV]</td>
<td>0.3</td>
<td>0.07</td>
<td>44</td>
<td>6.2</td>
<td>65</td>
<td>95</td>
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</table>

LEP data for 94.5 - 101 GeV consistently suggest a beam-beam limit of ~0.115 (R.Assmann, K. C.)
beam lifetime

LEP2:
- beam lifetime $\sim 6 \text{ h}$
- dominated by radiative Bhabha scattering with cross section $\sigma \sim 0.215$ barn [11]

LEP3:
- with $L \sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ at each of two IPs:
  \[ \tau_{\text{beam,LEP3}} \sim 18 \text{ minutes} \]
- additional beam lifetime limit due to beamstrahlung requires large momentum acceptance ($\delta_{\text{max,RF}} \geq 3\%$) and/or flat beams and/or fast replenishing
  (Valery Telnov, Kaoru Yokoya, Marco Zanetti)
note: beamstrahlung effect at LEP3 much smaller than for ILC, \( \sim \) monochromatic luminosity profile

\[ \text{LEP3, } L_{0.01} = 1.0 \]

\[ \text{ILC, } L_{0.01} = 0.86 \]
LEP3/TLEP: **double ring w. top-up injection** supports short lifetime & high luminosity

A. Blondel

![Diagram of accelerator and collider rings](image)

A first ring accelerates electrons and positrons up to operating energy (120 GeV) and injects them at a few minutes interval into the low-emittance collider ring, which includes high luminosity $\geq 10^{34}$ cm$^{-2}$ s$^{-1}$ interaction points.
top-up injection: $e^+$ production

top-up interval $<<$ beam lifetime

→ average luminosity $\approx$ peak luminosity!

LEP3 needs about $4 \times 10^{12}$ $e^+$ every few minutes, or of order $2 \times 10^{10}$ $e^+$ per second

for comparison:

LEP injector complex delivered of order $10^{11}$ $e^+$ per second (5x more than needed for LEP3!)
top-up injection: magnet ramp

**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**


LEP3/TLEP: with injection from SPS into top-up accelerator at 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 $\tau_{\text{beam}} \sim 16$ min)

Ghislain Roy & Paul Collier
top-up injection: schematic cycle

beam current in collider (15 min. beam lifetime)
- 100%
- 99%
- almost constant current

energy of accelerator ring
- 120 GeV
- 20 GeV

injection into collider
injection into accelerator
10 s
two schematic time schedules for LEP3

Of course TLEP would be constructed independently and would pave direct path for VHE-LHC.
LEP3/TLEP R&D items

- choice of RF frequency: 1.3 GHz or 700 MHz? & RF coupler
- SR handling and radiation shielding (LEP experience)
- beam-beam interaction for large $Q_s$ and significant hourglass effect
- IR design with large momentum acceptance
- integration in LHC tunnel (LEP3)
**summary of LEP3/TLEP physics measurements**

- **Comparison with LHC and HL-LHC**
  
  (CMS and SFitter projections)

<table>
<thead>
<tr>
<th></th>
<th>ILC</th>
<th>LEP3 (2)</th>
<th>LEP3 (4)</th>
<th>TLEP (2)</th>
<th>LHC (300)</th>
<th>HL-LHC</th>
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<td>$\sigma_{HZ}$</td>
<td>3%</td>
<td>1.9%</td>
<td>1.3%</td>
<td>0.7%</td>
<td>–</td>
<td>–</td>
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<td>$\sigma_{HZ} \times \text{BR}(H \rightarrow b\bar{b})$</td>
<td>1%</td>
<td>0.8%</td>
<td>0.5%</td>
<td>0.2%</td>
<td>–</td>
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<td>$\sigma_{HZ} \times \text{BR}(H \rightarrow \tau^+\tau^-)$</td>
<td>6%</td>
<td>3.0%</td>
<td>2.2%</td>
<td>1.3%</td>
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<td>$\sigma_{HZ} \times \text{BR}(H \rightarrow W^+W^-)$</td>
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<td>3.6%</td>
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<td>1.6%</td>
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<td>–</td>
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<tr>
<td>$\sigma_{HZ} \times \text{BR}(H \rightarrow \gamma\gamma)$</td>
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<td>9.5%</td>
<td>6.6%</td>
<td>4.2%</td>
<td>–</td>
<td>–</td>
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<tr>
<td>$\sigma_{HZ} \times \text{BR}(H \rightarrow \mu^+\mu^-)$</td>
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<td>–</td>
<td>28%</td>
<td>17%</td>
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<td>0.7%</td>
<td>0.4%</td>
<td>–</td>
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<td>$\delta_{HZZ}$</td>
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<td>0.9%</td>
<td>0.6%</td>
<td>0.3%</td>
<td>13%/5.7%</td>
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</tr>
<tr>
<td>$\delta_{H\tau\tau}$</td>
<td>3%</td>
<td>2.0%</td>
<td>1.5%</td>
<td>0.6%</td>
<td>13%/8.5%</td>
<td>5.4%</td>
</tr>
<tr>
<td>$\delta_{Hcc}$</td>
<td>4%</td>
<td>?</td>
<td>?</td>
<td>0.9%</td>
<td>?/?</td>
<td>?</td>
</tr>
<tr>
<td>$\delta_{HWW}$</td>
<td>4%</td>
<td>2.2%</td>
<td>1.5%</td>
<td>0.9%</td>
<td>11%/5.7%</td>
<td>4.5%</td>
</tr>
<tr>
<td>$\delta_{H\gamma\gamma}$</td>
<td>?</td>
<td>4.9%</td>
<td>3.4%</td>
<td>2.2%</td>
<td>?/6.5%</td>
<td>5.4%</td>
</tr>
<tr>
<td>$\delta_{H\mu\mu}$</td>
<td>–</td>
<td>–</td>
<td>14%</td>
<td>9%</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>$\delta_{Htt}$</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>14%</td>
<td>8%</td>
</tr>
<tr>
<td>$m_H$ (MeV/c²)</td>
<td>50</td>
<td>37</td>
<td>26</td>
<td>11</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

- LEP3/TLEP exceed substantially LHC sensitivity
  
  ➤ Even in its highest luminosity version

P. Janot, CERN PH seminar 30 October, attended and watched by >400 physicists
circular $e^+e^-$ Higgs factories become popular around the world
LEP3/TLEP baseline w established technology

I had thought (and still think) that the possible use of cheap, robust, established technology is a great asset for LEP3/TLEP

However, in Cracow the argument has been put forward that any future collider should be a Hi-Tech facility (i.e. ~18 GV SRF not enough, 350 GeV SRF being much better! - In other words a reasoning that we should fill a large tunnel with expensive objects instead of with cheap “concrete” magnets like LEP/LEP2)
by the way, LEP2 technology worked well

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design LEP1 / LEP2</th>
<th>Achieved LEP1 / LEP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch current</td>
<td>0.75 mA</td>
<td>1.00 mA</td>
</tr>
<tr>
<td>Total beam current</td>
<td>6.0 mA</td>
<td>8.4 / 6.2 mA</td>
</tr>
<tr>
<td>Vertical beam-beam parameter</td>
<td>0.03</td>
<td>0.045 / 0.083</td>
</tr>
<tr>
<td>Emittance ratio</td>
<td>4.0 %</td>
<td>0.4 %</td>
</tr>
<tr>
<td>Maximum luminosity</td>
<td>$16 / 27 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$</td>
<td>$34 / 100 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$</td>
</tr>
<tr>
<td>IP beta function $\beta_x$</td>
<td>1.75 m</td>
<td>1.25 m</td>
</tr>
<tr>
<td>IP beta function $\beta_y$</td>
<td>7.0 cm</td>
<td>4.0 cm</td>
</tr>
<tr>
<td>Max. beam energy</td>
<td>95 GeV</td>
<td>104.5 GeV</td>
</tr>
<tr>
<td>Av. RF gradient</td>
<td>6.0 MV/m</td>
<td>7.2 MV/m</td>
</tr>
</tbody>
</table>
LEP3/TLEP(/VHE-LHC) hi-tech options

examples-

novel SC cavities for LEP3/TLEP collider

fast ramping HTS magnets
for LEP3/TLEP double ring

VHE-LHC 20-T high-field magnets
SC cavities based on material other than bulk niobium e.g. thin films or $Nb_3Sn$

- extensive studies at CERN (T. Junginger) and JLAB
- CERN/Legnaro/Sheffield cavities - first prototypes tested at Legnaro in 2012! HiPIMS technique; SIS concept,…
- sputtered $Nb$ will reduce cost & may show better performance; even more HTS SIS cavities
- $Nb_3Sn$ could be studied at CERN (quad resonator) in collaboration with other labs

E. Jensen, LHeC 2012; JLAB, IPAC12

Hi-Tech cavities!

micrographs of sample surface of a micrometer thin niobium film sputtered on top of a copper substrate (left) and a bulk niobium (right) sample

T. Junginger et al, IPAC2011
fast ramping 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: $B_{\text{max}} = 0.5 \ T$, $I_{\text{max}} = 27 \ \text{kA}$, $\frac{dB}{dt}_{\text{max}} = 10 \ \text{T/s}$, $T_{\text{max}} \sim 25 \ \text{K}$

acceleration time $\sim 0.1 \ \text{s}$, total cycle $\sim 1 \ \text{s}$; fast SC magnets might support 1 minute lifetime in collider ring!
(V)HE-LHC 20-T hybrid magnet

block layout of Nb-Ti & Nb$_3$Sn & HTS (Bi-2212) 20-T dipole-magnet coil. Only one quarter of one aperture is shown.
example opinion on LEP3/TLEP

«a ring e⁺e⁻ collider LEP3 or TLEP can provide an economical and robust solution with higher statistics than LC and >1 IP for studying the X(125) with high precision and doing many precision measurements on H, W, Z (+top quark) within our lifetimes»

Alain Blondel

ATLAS Meeting
4 Oct. 2012
Part 2 - SAPPHiRE
“Higgs” strongly couples to $\gamma\gamma$
a new type of collider?

\[ \gamma \rightarrow t, W, \ldots \]

\[ H \]

\[ \gamma \gamma \]

\[ s\text{-channel production}; \]
\[ \text{lower energy}; \]
\[ \text{no } e^+ \text{ source} \]

another advantage:

\[ \text{no beamstrahlung} \]
\[ \rightarrow \text{higher energy reach} \]
\[ \text{than } e^+e^- \text{ colliders} \]

\[ \gamma\gamma \text{ collider Higgs factory} \]
Combining photon science & particle physics!

$\gamma \gamma$ collider

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

Few $J$ pulse energy with $\lambda \sim 350$ nm
which beam & photon energy / wavelength?

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

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

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

\( E_{\text{photon}} \sim 3.53 \text{ eV} , \lambda \sim 351 \text{ nm} \)
luminosity spectra for SAPPHiRE as functions of $E_{CM}(\gamma\gamma)$, computed using Guinea-Pig for three possible normalized distances $\rho \equiv l_{CP-IP}/(\gamma\sigma_{\gamma \gamma}^*)$ (left) and different polarizations of in-coming particles (right)
Higgs $\gamma\gamma$ production cross section

Left: The cross sections for $\gamma\gamma \rightarrow h$ for different values of $M_h$ as functions of $E_{cm}(e^-e^-)$.

Right: The cross section for $\gamma\gamma \rightarrow h$ as a function of $M_h$ for three different values of $E_{cm}(e^-e^-)$.

Assumptions: electrons have 80% longitudinal polarization and lasers are circularly polarized, so that produced photons are highly circularly polarized at their maximum energy.
Laser progress: example fiber lasers

Power evolution of cw double-clad fiber lasers with diffraction limited beam quality over one decade: factor 400 increase!

Source: Fiber Based High Power Laser Systems, Jens Limpert, Thomas Schreiber, and Andreas Tünnermann
passive optical cavity

→

relaxed

laser

parameters

K. Moenig et al, DESY Zeuthen
self-generated FEL $\gamma$ beams (instead of laser)!

- **Wiggler**
  - Converting some $e^-$ energy into photons ($\lambda \approx 350$ nm)

  

example: $\lambda_u = 50$ cm, $B = 5$ T, $L_u = 50$ m, 0.1% $P_{\text{beam}} \approx 25$ kW

"intracavity powers at MW levels are perfectly reasonable" – D. Douglas, 23 August 2012

scheme developed with Z. Huang
SAPPHiRE: a Small $\gamma\gamma$ Higgs Factory

scale ~ European XFEL, about 10k Higgs per year

total circumference ~ 9 km

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

SAPPHiRE: Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons
<table>
<thead>
<tr>
<th>SAPPHiRE</th>
<th>symbol</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>total electric power</td>
<td>$P$</td>
<td>100 MW</td>
</tr>
<tr>
<td>beam energy</td>
<td>$E$</td>
<td>80 GeV</td>
</tr>
<tr>
<td>beam polarization</td>
<td>$P_e$</td>
<td>0.80</td>
</tr>
<tr>
<td>bunch population</td>
<td>$N_b$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>repetition rate</td>
<td>$f_{rep}$</td>
<td>200 kHz</td>
</tr>
<tr>
<td>bunch length</td>
<td>$\sigma_z$</td>
<td>30 µm</td>
</tr>
<tr>
<td>crossing angle</td>
<td>$\theta_c$</td>
<td>$\geq$20 mrad</td>
</tr>
<tr>
<td>normalized horizontal/vert. emittance</td>
<td>$\gamma \varepsilon_{x,y}$</td>
<td>5,0.5 µm</td>
</tr>
<tr>
<td>horizontal IP beta function</td>
<td>$\beta_x^*$</td>
<td>5 mm</td>
</tr>
<tr>
<td>vertical IP beta function</td>
<td>$\beta_y^*$</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>horizontal rms IP spot size</td>
<td>$\sigma_x^*$</td>
<td>400 nm</td>
</tr>
<tr>
<td>vertical rms IP spot size</td>
<td>$\sigma_y^*$</td>
<td>18 nm</td>
</tr>
<tr>
<td>horizontal rms CP spot size</td>
<td>$\sigma_x^{CP}$</td>
<td>400 nm</td>
</tr>
<tr>
<td>vertical rms CP spot size</td>
<td>$\sigma_y^{CP}$</td>
<td>180 nm</td>
</tr>
<tr>
<td>e⁻e⁻ geometric luminosity</td>
<td>$L_{ee}$</td>
<td>$2 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
</tbody>
</table>
Energy loss on multiple passes

The energy loss per arc is $\Delta E_{arc} [\text{GeV}] = 8.846 \times 10^{-5} \left( \frac{E [\text{GeV}]}{2 \rho [\text{m}]} \right)^4$.

For $\rho = 764$ m (LHeC design) the energy loss in the various arcs is summarized in the following table. e- lose about 4 GeV in energy, which can be compensated by increasing the voltage of the two linacs from 10 GV to 10.5 GV. We take 11 GV per linac to be conservative.

<table>
<thead>
<tr>
<th>beam energy [GeV]</th>
<th>$\Delta E_{arc}$ [GeV]</th>
<th>$\Delta \sigma_E$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.0006</td>
<td>0.038</td>
</tr>
<tr>
<td>20</td>
<td>0.009</td>
<td>0.43</td>
</tr>
<tr>
<td>30</td>
<td>0.05</td>
<td>1.7</td>
</tr>
<tr>
<td>40</td>
<td>0.15</td>
<td>5.0</td>
</tr>
<tr>
<td>50</td>
<td>0.36</td>
<td>10</td>
</tr>
<tr>
<td>60</td>
<td>0.75</td>
<td>20</td>
</tr>
<tr>
<td>70</td>
<td>1.39</td>
<td>35</td>
</tr>
<tr>
<td>80</td>
<td>1.19</td>
<td>27</td>
</tr>
<tr>
<td>total</td>
<td>3.89</td>
<td>57 (0.071%)</td>
</tr>
</tbody>
</table>
The emittance growth is $\Delta \varepsilon_N = \frac{2\pi C_q r_e}{3 \rho^2} \gamma^6 \langle H \rangle$

with $C_q=3.8319 \times 10^{-13}$ m, and $\rho$ the bending radius.

For LHeC RLA design with $l_{\text{bend}} \sim 10$ m, and $\rho=764$ m, $\langle H \rangle=1.2 \times 10^{-3}$ m [Bogacz et al]. At 60 GeV the emittance growth of LHeC optics is 13 micron, too high for our purpose, and extrapolation to 80 GeV is unfavourable with 6th power of energy. From L. Teng we also have scaling law $\langle H \rangle \propto l_{\text{bend}}^3 / \rho^2$, which suggests that by reducing the cell length and dipole length by a factor of 4 we can bring the horiz. norm. emittance growth at 80 GeV down to 1 micron.

Valery Telnov thinks this scaling is too optimistic.
Minimizing the Emittance in Designing the Lattice of an Electron Storage Ring

L.C. Teng

June 1984
flat polarized electron source

- target $\varepsilon_x/\varepsilon_y \sim 10$
- flat-beam gun based on flat-beam transformer concept of Derbenev et al.
- starting with $\gamma \varepsilon \sim 4-5 \, \mu m$ at 0.5 nC, injector test facility at Fermilab A0 line achieved emittances of 40 $\mu m$ horizontally and 0.4 $\mu m$ vertically, with $\varepsilon_x/\varepsilon_y \sim 100$
- for SAPPHiRE we only need $\varepsilon_x/\varepsilon_y \sim 10$, but at three times larger bunch charge (1.6 nC) and smaller initial $\gamma \varepsilon \sim 1.5 \, \mu m$
- these parameters are within the present state of the art (e.g. the LCLS photoinjector routinely achieves 1.2 $\mu m$ emittance at 1 nC charge)
- however, we need a polarized beam...

Valery Telnov stressed this difficulty
can we get ~ 1-nC polarized $e^-$ bunches with ~1 μm emittance?

ongoing R&D efforts:

**low-emittance DC guns**
(MIT-Bates, Cornell, SACLA, JAEA, KEK...)

[E. Tsentalovich, I. Bazarov, et al]

**polarized SRF guns** (FZD, BNL,...)

[J. Teichert, J. Kewisch, et al]
LHeC → SAPPHiRE

Schematic sketches of the layout for the LHeC ERL (left) and for a gamma-gamma Higgs factory based on the LHeC (right)
would it fit on SLAC site?
schematic of HERA-$\gamma\gamma$

- 5.6 GeV
  - 15.8
  - 26.0
  - 36.2
  - 46.0
  - 55.3
  - 63.8
  - 71.1
  - 71.1
  - 63.8
  - 55.2
  - 46.0
  - 36.2
  - 26.0
  - 15.8
  - 5.6

- 75.8 GeV

- 20-MV deflecting cavity (1.3 GHz)
- 3.6 GeV linac
- 2x1.5 GeV linac
- 0.5 GeV injector
- 2x8+1 arcs
- IP
- laser or auto-driven FEL

- $\rho=564$ m for arc dipoles (probably pessimistic; value assumed in the following)

F. Zimmermann, R. Assmann, E. Elsen,
DESY Bschleuniger-Ideenmarkt, 18 Sept. 2012
γγ Collider at J-Lab

By Edward Nissen
Town Hall meeting Dec 19 2011

similar ideas elsewhere
Background

\[ x = \frac{12.3 E_e (TeV)}{\lambda_\gamma (\mu m)} \]

\[ \hbar \omega_\gamma = \frac{x}{1+x} E_e \]

Figure 5: Cross sections for the Standard model Higgs in \( \gamma \gamma \) and \( e^+e^- \) collisions.

arXiv:hep-ex/9802003v2
Possible Configurations at JLAB

85 GeV Electron energy
\( \gamma \) c.o.m. 141 GeV

103 GeV Electron energy
\( \gamma \) c.o.m. 170 GeV
SAPPHiRE R&D items

- γγ interaction region
- large high-finesse optical cavity
- high repetition rate laser
- FEL in unusual regime
- separation scheme for beams circulating in opposite directions
## vertical rms IP spot sizes in nm

<table>
<thead>
<tr>
<th>Facility</th>
<th>Size (nm)</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>LEP3</td>
<td>320</td>
</tr>
<tr>
<td>TLEP-H</td>
<td>220</td>
</tr>
<tr>
<td>ATF2, FFTB</td>
<td>150±, 65</td>
</tr>
<tr>
<td>SuperKEKB</td>
<td>50</td>
</tr>
<tr>
<td>SAPPHiRE</td>
<td>18</td>
</tr>
<tr>
<td>ILC</td>
<td>5</td>
</tr>
<tr>
<td>CLIC</td>
<td>1</td>
</tr>
</tbody>
</table>
Conclusions

LEP3, TLEP and SAPPHiRE are exciting and popular projects

LEP3 and SAPPHiRE appear to be the cheapest possible options to study the Higgs (cost \(\sim 1\) BEuro scale), feasible, “off the shelf”, but not easy

TLEP is more expensive (\(\sim 5\) BEuro?), but superior (energy & luminosity), and it would be extendable towards VHE-LHC, preparing \(\geq 50\) years of exciting \(e^+e^-, pp, ep/A\) physics at highest energies
LEP3, TLEP, and SAPPHiRE are moving forward – please join

thank you for listening!

J. Adams, 1959
References for LEP3/TLEP:
References for SAPPHiRE:


backup slides
rf efficiency \( (P_{\text{wall}} \rightarrow P_{SR}) \)


conversion efficiency grid to amplifier RF output = 70%
transmission losses = 7%
feedbacks power margin = 15%
→ **total efficiency ~55%**

50% assumed for LEP3/TLEP at same frequency & gradient
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)
beam-beam with large hourglass effect?
simulations by K. Ohmi presented at 2nd EuCARD LEP3 Day