LEP3 and TLEP

Zimmermann, F (CERN, Geneva, Switzerland)

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LEP3 and TLEP

Frank Zimmermann

HF2012, FNAL, 15 November 2012


work supported by the European Commission under the FP7 Research Infrastructures project EuCARD, grant agreement no. 227579
circular Higgs factories at CERN & beyond

LEP3
($e^+e^-$, 240 GeV c.m.)

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

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

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

*a long-term strategy for HEP!*
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 “TLEP”
  + higher energy reach, 5-10x higher luminosity
  + decoupled from LHC/HL-LHC operation & construction
  + tunnel can later serve for HE-LHC (factor 3 in energy from tunnel alone) with LHC remaining as injector
  - 4-5x more expensive (new tunnel, cryoplants, detectors)
LEP3, TLEP

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

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 at 350 GeV c.m.</td>
<td>-</td>
<td>0.7x10^{34} cm^{-2}s^{-1}</td>
</tr>
<tr>
<td>luminosity at 240 GeV c.m.</td>
<td>10^{34} cm^{-2}s^{-1}</td>
<td>5x10^{34} cm^{-2}s^{-1}</td>
</tr>
<tr>
<td>luminosity at 160 GeV c.m.</td>
<td>5x10^{34} cm^{-2}s^{-1}</td>
<td>2.5x10^{35} cm^{-2}s^{-1}</td>
</tr>
<tr>
<td>luminosity at 90 GeV c.m.</td>
<td>2x10^{35} cm^{-2}s^{-1}</td>
<td>10^{36} cm^{-2}s^{-1}</td>
</tr>
</tbody>
</table>

at the Z pole repeating LEP physics programme in a few minutes...
arc optics
- same as for LHeC: $\epsilon_{x,LHeC} < \frac{1}{3} \epsilon_{x,LEP1.5}$ at equal beam energy,
- optical structure compatible with present LHC machine (not optimum!)
- small momentum compaction (short bunch length)
- assume $\epsilon_y/\epsilon_x \sim 5 \times 10^{-3}$ similar to LEP (ultimate limit $\epsilon_y \sim 1$ 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 $\leq$ LHC

synchrotron radiation
- energy loss / turn: $E_{\text{loss}}[\text{GeV}] = 88.5 \times 10^{-6} \left( E_b[\text{GeV}] \right)^4 / \rho[\text{m}]$.
- 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
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?

particle rates in Hz/cm²

RPC OUTER:
- $n_1$: 2380, $e/\pi$: 7.7, $\mu$: 0.3
- $n_2$: 289, $e/\pi$: 0.4
- $n_3$: 41, $e/\pi$: 0
- $\gamma$: 1050

RPC MID:
- $n_1$: 2320, $e/\pi$: 11
- $n_2$: 362, $e/\pi$: 1.5
- $n_3$: 18, $e/\pi$: 1.1
- $\gamma$: 980

MDT IN:
- LowZ
- MidZ
- HighZ

LW MDT
- $n_1$: 3581, $e/\pi$: 9.9
- $n_2$: 409, $e/\pi$: 0.4
- $n_3$: 101, $e/\pi$: 1.0
- $\gamma$: 1280
- $\gamma$: 1460

BW MDT
- $n_1$: 1330, $e/\pi$: 5.0
- $n_2$: 351, $e/\pi$: 0.5
- $n_3$: 49

Based on M. Nessi CARE-HHH IR'07

Integration of LEP3 IR in the ATLAS detector is discussed.
activation of LHC tunnel after (HL-) LHC operation

Activation of Arcs

Assumption:

$2.4 \times 10^4$ protons/m/s (both beams), 7TeV, lost for 180 days continuously (corresponds to an H$_2$-equivalent beam gas density of $4.5 \times 10^{14}$ /m$^3$)

"Operation of HE-LHC will not increase the radiological risk to workers and public when compared to LHC-ultimate and HL-LHC (based on best present knowledge)"

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 km ring

TLEP tunnel in the KEK area?

12.3 km

Proposal by K. Oide, 13 February 2012
80 km ring in KEK area

KEK

12.7 km
105 km tunnel near FNAL

H. Piekarz, “... and ... path to the future of high energy particle physics,” JINST 4, P08007 (2009)
luminosity formulae & constraints

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

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

\[ N_b = \xi_x 2\pi \gamma (1 + \kappa_\sigma) \quad \text{beam-beam limit} \]

\[ \varepsilon_x \quad r_e \]

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

\[ \rightarrow \text{minimize } \kappa_\varepsilon = \varepsilon_y / \varepsilon_x, \quad \beta_y \sim \beta_x (\varepsilon_y / \varepsilon_x) \quad \text{and respect } \beta_y \geq \sigma_z \]
<table>
<thead>
<tr>
<th></th>
<th>LEP2</th>
<th>LHeC</th>
<th>LEP3</th>
<th>TLEP-Z</th>
<th>TLEP-H</th>
<th>TLEP-t</th>
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<tbody>
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<td>beam energy Eb [GeV]</td>
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<td>45.5</td>
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<td>26.7</td>
<td>26.7</td>
<td>80</td>
<td>80</td>
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<tr>
<td>beam current [mA]</td>
<td>4</td>
<td>100</td>
<td>7.2</td>
<td>1180</td>
<td>24.3</td>
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<td>#bunches/beam</td>
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<td>2808</td>
<td>4</td>
<td>2625</td>
<td>80</td>
<td>12</td>
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<td>#e-/beam $[10^{12}]$</td>
<td>2.3</td>
<td>56</td>
<td>4.0</td>
<td>2000</td>
<td>40.5</td>
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<td>horizontal emittance [nm]</td>
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<td>5</td>
<td>25</td>
<td>30.8</td>
<td>9.4</td>
<td>20</td>
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<td>0.25</td>
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<td>0.10</td>
<td>0.15</td>
<td>0.05</td>
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<td>9.0</td>
<td>9.0</td>
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<td>1.5</td>
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<td>9.0</td>
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<td>44</td>
<td>50</td>
<td>50</td>
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<td>$\beta_x^* [m]$</td>
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<td>0.18</td>
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<td>$\beta_y^* [cm]$</td>
<td>5</td>
<td>10</td>
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<td>$\sigma_x^* [\mu m]$</td>
<td>270</td>
<td>30</td>
<td>71</td>
<td>78</td>
<td>43</td>
<td>63</td>
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<tr>
<td>$\sigma_y^* [\mu m]$</td>
<td>3.5</td>
<td>16</td>
<td>0.32</td>
<td>0.39</td>
<td>0.22</td>
<td>0.32</td>
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<td>hourglass $F_{hg}$</td>
<td>0.98</td>
<td>0.99</td>
<td>0.59</td>
<td>0.71</td>
<td>0.75</td>
<td>0.65</td>
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<tr>
<td>$\Delta E_{SR}^{loss}/\text{turn} [\text{GeV}]$</td>
<td>3.41</td>
<td>0.44</td>
<td>6.99</td>
<td>0.04</td>
<td>2.1</td>
<td>9.3</td>
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<td>Parameter</td>
<td>LEP2</td>
<td>LHeC</td>
<td>LEP3</td>
<td>TLEP-Z</td>
<td>TLEP-H</td>
<td>TLEP-t</td>
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<td>---------------------------------</td>
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<tr>
<td>$V_{RF,tot}$ [GV]</td>
<td>3.64</td>
<td>0.5</td>
<td>12.0</td>
<td>2.0</td>
<td>6.0</td>
<td>12.0</td>
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<td>$\delta_{max,RF}$ [%]</td>
<td>0.77</td>
<td>0.66</td>
<td>5.7</td>
<td>4.0</td>
<td>9.4</td>
<td>4.9</td>
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<td>$\xi_x/IP$</td>
<td>0.025</td>
<td>N/A</td>
<td>0.09</td>
<td>0.12</td>
<td>0.10</td>
<td>0.05</td>
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<td>$\xi_y/IP$</td>
<td>0.065</td>
<td>N/A</td>
<td>0.08</td>
<td>0.12</td>
<td>0.10</td>
<td>0.05</td>
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<td>$f_s$ [kHz]</td>
<td>1.6</td>
<td>0.65</td>
<td>2.19</td>
<td>1.29</td>
<td>0.44</td>
<td>0.43</td>
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<td>$E_{acc}$ [MV/m]</td>
<td>7.5</td>
<td>11.9</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
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<tr>
<td>eff. RF length [m]</td>
<td>485</td>
<td>42</td>
<td>600</td>
<td>100</td>
<td>300</td>
<td>600</td>
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<tr>
<td>$f_{RF}$ [MHz]</td>
<td>352</td>
<td>721</td>
<td>700</td>
<td>700</td>
<td>700</td>
<td>700</td>
</tr>
<tr>
<td>$\sigma_{SR}$ [cm]</td>
<td>1.61</td>
<td>0.69</td>
<td>0.31</td>
<td>0.19</td>
<td>0.17</td>
<td>0.25</td>
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<tr>
<td>$\sigma_{SR,z,rms}$ [cm]</td>
<td>0.22</td>
<td>0.12</td>
<td>0.23</td>
<td>0.06</td>
<td>0.15</td>
<td>0.22</td>
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<tr>
<td>$L/IP [10^{32} cm^{-2}s^{-1}]$</td>
<td>1.25</td>
<td>N/A</td>
<td>94</td>
<td>10335</td>
<td>490</td>
<td>65</td>
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<tr>
<td>number of IPs</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Rad.Bhabha b.lifetime [min]</td>
<td>360</td>
<td>N/A</td>
<td>18</td>
<td>74</td>
<td>32</td>
<td>54</td>
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<tr>
<td>$\gamma_{BS}$ [10^{-4}]</td>
<td>0.2</td>
<td>0.05</td>
<td>9</td>
<td>4</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>$n_{\gamma}$ /collision</td>
<td>0.08</td>
<td>0.16</td>
<td>0.60</td>
<td>0.41</td>
<td>0.50</td>
<td>0.51</td>
</tr>
<tr>
<td>$\Delta \delta_{BS}$ /collision [MeV]</td>
<td>0.1</td>
<td>0.02</td>
<td>31</td>
<td>3.6</td>
<td>42</td>
<td>61</td>
</tr>
<tr>
<td>$\Delta \delta_{BS,rms}$ /collision [MeV]</td>
<td>0.3</td>
<td>0.07</td>
<td>44</td>
<td>6.2</td>
<td>65</td>
<td>95</td>
</tr>
</tbody>
</table>

LEP2 was not beam-beam limited.

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 ~ 6 h
• dominated by radiative Bhabha scattering with cross section $\sigma \sim 0.215$ barn

LEP3:
• with $L \sim 10^{34}$ cm$^{-2}$s$^{-1}$ at each of two IPs:
  $\tau_{\text{beam,LEP3}} \sim 18$ minutes from rad. Bhabha
• additional beam lifetime limit due to beamstrahlung requires: (1) large momentum acceptance ($\delta_{\text{max,RF}} \geq 3\%$), and/or (2) flat(ter) beams and/or (3) fast replenishing

(Valery Telnov, Kaoru Yokoya, Marco Zanetti)
**energy spectrum after 1 collision**

- GUINEA-PIG simulation with 360M macroparticles
- lifetime depends exponentially on energy acceptance $\eta$

- as for LEP3, TLEP BS lifetime well above required threshold
- in particular there is some margin for TLEP-H

M. Zanetti, MIT
2nd LEP3 Day
note: beamstrahlung effect at LEP3 much smaller than for ILC, \(~\)monochromatic luminosity profile

beamstrahlung much more benign than for linear collider; LEP3/TLEP are clean machines

M. Zanetti, MIT
2nd LEP3 Day
LEP3/TLEP: double ring w. top-up injection supports short lifetime & high luminosity

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 $\ll$ beam lifetime

$\rightarrow$ 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 $\sim 10^{11}$ $e^+$ 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 $\tau_{\text{beam}} \sim 18$ min)

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

beam current in collider (15 min. beam lifetime)

energy of accelerator ring

120 GeV

20 GeV

injection into collider

injection into accelerator

almost constant current

10 s
two schematic time schedules for LEP3

of course TLEP would be constructed independently and could pave a direct path to VHE-LHC
LEP3/TLEP R&D items

- choice of RF frequency: 1.3 GHz (ILC) or 700 MHz (ESS)? & 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)
- Pretzel scheme for TERA-Z operation
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 and here at FNAL 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 magnets as for 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 $10^{30}$ cm$^{-2}$s$^{-1}$</td>
<td>34 / 100 $10^{30}$ cm$^{-2}$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 Nb: thin Nb films, Nb$_3$Sn, HTS

- 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 & and may show better performance; even more HTS SIS** cavities
- Nb$_3$Sn could be studied at CERN (quad resonator) in collaboration with other labs

*High-power impulse magnetron sputtering, **Superconductor-Insulator-Superconductor

---

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

T. Junginger et al, IPAC2011
transmission-line HTS/LTS magnets

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

HTS prototype dipole at FNAL
Test: $B_{\text{max}} = 0.5 \, \text{T}$, $I_{\text{max}} = 27 \, \text{kA}$, $\frac{dB}{dt}_{\text{max}} = 10 \, \text{T/s}$, $T_{\text{max}} \sim 25 \, \text{K}$

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.
### vertical rms IP spot sizes in nm

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
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<td><strong>SLC</strong></td>
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<td>320</td>
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<td><strong>TLEP-H</strong></td>
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<tr>
<td><strong>ATF2, FFTB</strong></td>
<td>150? (35), 65</td>
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<tr>
<td><strong>SuperKEKB</strong></td>
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<tr>
<td><strong>SAPPHiRE</strong></td>
<td><strong>18</strong></td>
</tr>
<tr>
<td><strong>ILC</strong></td>
<td>5</td>
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<td><strong>CLIC</strong></td>
<td>1</td>
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**LEM3/TLEP** will learn a lot from **SuperKEKB** and **ATF2**!
a ring $e^+e^-$ collider LEP3 or TLEP appears to provide an economical & robust solution with very high statistics at several IPs for studying the $X(125)$ with excellent precision & for performing many high-resolution measurements on $H$, $W$, $Z$ (+top quark) within our lifetimes [A. Blondel];

LEP3/TLEP would be THE choice for $e^+e^-$ collision energies up to 400 GeV;

TLEP could be part of a long-term HEP strategy aiming for 100 TeV pp CoM energy
having the tunnel is everything!

quoting Nick Walker,
Conclusions:

**LEP3** may be the **cheapest possible option** to study the **Higgs** (cost ~1BEuro scale), feasible, “off the shelf”, but perhaps **not easy**

**TLEP** is **more expensive** (~5 BEuro?), but clearly superior in terms of energy & luminosity, and extendable towards VHE-LHC, preparing ≥50 years of exciting $e^+e^-$, $pp$, $ep/A$ physics at highest energies

**LEP3 and TLEP** offer interesting energy-frontier physics at **moderate cost and/or with long-term perspective**, using robust technology

**LEP3 and TLEP deserve a detailed design study**
thank you for listening!

"NOLI TURBARE CIRCULOS MEOS!"
Archimedes of Syracuse, 287 – 212 BC

(incidentally, the only appearance of a Roman in the history of mathematics)
References for LEP3/TLEP:


