

LEP3: A HIGH LUMINOSITY E+E- COLLIDER TO STUDY THE HIGGS BOSON

Submitted to the European Strategy Preparatory Group

A. Blondel, U. Geneva, Switzerland;

M. Koratzinos, Geneva, Switzerland;

R. W. Assmann, A. Butterworth, P. Janot, J. M. Jimenez, C. Grojean, A. Milanese, M. Modena, J.A. Osborne, F. Zimmermann, CERN, Geneva, Switzerland;

H. Piekarczyk, FNAL, U.S.A.;

K. Oide, K. Yokoya, KEK Japan;

J. Ellis, King's College London and CERN, Geneva, Switzerland;

M. Klute, M. Zanetti, MIT, Cambridge, Massachusetts, USA;

M. Velasco, Northwestern U., U.S.A.;

V. Telnov, Budker INP, Novosibirsk, Russia;

L. Rivkin, PSI, Villigen, Switzerland;

B. Murray, STFC, Rutherford Appleton Laboratory, UK;

Y. Cai, SLAC National Accelerator Laboratory, Stanford, U.S.A.

Abstract

The LHC experiments have discovered a new particle with a mass around 125 GeV that is a strong candidate for the scalar Higgs boson expected in the Standard Model. An e^+e^- collider operating close to the ZH threshold (at a centre-of-mass energy of 240 GeV) could be the tool of choice for studying this unique particle in detail.

We present here the concept of a storage ring collider, which we call LEP3. Preliminary studies show that at a centre-of-mass energy of 240 GeV, near-constant luminosities of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ are possible in up to four collision points, while respecting a number of constraints including beamstrahlung limits. With an integrated luminosity of 100fb^{-1} per year and per interaction point, 20,000 $e^+e^- \rightarrow \text{ZH}$ events would be produced per year and per experiment. LEP3 could also operate in multi-bunch mode at the Z resonance, with luminosities of several $\times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$, yielding $\mathcal{O}(10^{11})$ Z decays per year, as well as just above the WW threshold, potentially improving our knowledge of W and Z properties by large factors.

The short luminosity lifetime requires the use of top-up injection, which, in turn calls for a full-energy injector. Thus the present design uses two rings (as in the $\overline{\text{BB}}$ factories): a low-emittance collider storage ring operating at a constant energy, and a separate “accelerator” ring that tops up the collider ring every few minutes. The LHeC lattice design has been used as a basis for our studies. Maximum luminosity is achieved with four bunches per beam. The estimated beam lifetime is about 8 minutes (for four simultaneous experiments) dominated by e^+e^- Bhabha interactions. Finally the synchrotron radiation losses are 50 MW per beam. Further optimization of the design is possible.

LEP3 could be installed in the LHC tunnel, serving the two LHC general-purpose detectors ATLAS and CMS, and possibly up to two dedicated ILC-type detectors. Alternatively, it could be installed in a new, longer tunnel; using a tunnel circumference of 80km, a machine operating up to the $t\bar{t}$ threshold can be conceived.

This preliminary study has identified no show-stoppers for the concept of the design. A number of basic questions about LEP3 are discussed and we have tried to identify the areas where R&D will be needed.

We consider the concept to be highly interesting and deserving of a detailed study.

INTRODUCTION

In a seminal paper [1], B. Richter considered the limits of e^+e^- storage ring colliders, and concluded that such a machine could be achieved at up to 200 GeV centre-of-mass (E_{CM}) energy with a luminosity of $10^{32} \text{ cm}^{-2}\text{s}^{-1}$ – LEP indeed achieved just that. As an alternative to e^+e^- storage rings for higher energies, linear colliders have been discussed since the seminal paper of M. Tigner in 1965 [2], and U. Amaldi’s proposed design in 1976 [3] looks very much like today’s designs. At the time of LEP, the LEP2 top energy was considered to be a crossing point with a similar luminosity for the two concepts [4], above which the linear machine would become the only possibility due to the excessive synchrotron radiation in circular machines. Since then, linear collider studies have been optimized and offer luminosities of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ at 500 GeV. Meanwhile, however, circular machines have also made considerable progress with respect to the LEP design, with the introduction of much stronger focusing at the interaction points, multi-bunching, and, after successful demonstration of top-up injection at PEP-II and KEKB, the possibility of adding to the collider ring an independent accelerator topping up the storage ring. We should also mention the work done in the VLLC context, a design for a 370 GeV e^+e^- collider in a 233 km circumference tunnel [5]. Now that the LHC experiments have discovered a new particle that is a very good candidate for the Standard Model Higgs boson [6] [7], a very important particle that should definitely be studied in great detail, we consider it interesting to revisit the possibility offered by the well-known circular machines; indeed, LEP’s E_{CM} was only a fraction lower than what would have been needed for Higgs production.

The machine that we discuss which we call LEP3 [8] [9], is a very preliminary design that we consider so interesting that that it deserves an in-depth study, in particular because we expect it to be substantially more economical than a linear collider Higgs factory. The existence of show-stoppers cannot yet be excluded, but it is also possible that further optimization will make it even more interesting. As matters stand, we have been able to establish a set of parameters for a 240 GeV centre-of-mass ring collider operating with four bunches in each beam that would be able to deliver 100fb^{-1} per year to each of up to four collision points, including the multipurpose LHC experiments CMS and ATLAS as well as up to two ILC-type detectors, with a power dissipation of 50 MW per beam. The ability to deliver luminosity to more than one experiment is, in our view, a definite advantage of the circular machine over a linear one.

Most of the measurements of the Higgs mass, width and couplings that have been advertised to be achievable at a linear collider [10] [11] could be performed with even better precision at LEP3, with the exceptions of the Htt coupling, the HWW coupling and the triple Higgs coupling. However, we note that the Htt coupling is readily accessible at the LHC, either directly through the associated production process or indirectly through the $gg \rightarrow H$ production mechanism and the $H \rightarrow \gamma\gamma$ decay, and the HWW coupling is accessible directly via the vector-boson fusion (VBF) process, as well as via $H \rightarrow WW$ decays and indirectly via the $H \rightarrow \gamma\gamma$ decay. What remains is the triple Higgs coupling, which is both very fundamental and very difficult to determine either at LHC or at a linear collider – a precision of $\sim \pm 20\%$ has been advertised. It will be key to understand better the capabilities of the LHC experiments in this domain. On the other hand, the threshold $e^+e^- \rightarrow ZH$ threshold is unique in offering a Z tag which can be used to search for rare, unconventional or invisible H decays and the capacity for physics beyond the Standard Model of such a machine should not be underestimated.

Soon after LEP3 was proposed, it was suggested that a longer-term strategy could be developed: if an 80km tunnel could be made available, it would be possible to repeat the successful history of the LEP/LHC tunnel. At first a circular machine based on the LEP3 design (Triple-LEP or TLEP in the following) could be hosted, with a performance even superior to LEP3 in the LHC tunnel at the ZH threshold and with the added advantage of reaching the 350 GeV E_{CM} $t\bar{t}$ threshold. This would also make possible a precision top-quark mass measurement and access to the $e^+e^- \rightarrow WW \rightarrow H\nu\nu$ channel, enabling the HWW coupling to be determined with high precision. On a longer time scale, the 80 km tunnel could host an 80 TeV hadron collider, should 16T magnets become available, or a 40-TeV collider with LHC-type magnets, and might also be used to provide lepton-hadron collisions with the protons circulating in the LHC with both electrons and positrons of equal intensity, at higher luminosity than foreseen in the LHeC, and at higher lepton energy, e.g. 80 or 100 GeV instead of 60 GeV.

In either case the high performance achievable with the ring e^+e^- collider makes it worthy of a detailed study.

THE PHYSICS CASE

The LEP3 physics programme would consist of three (or four in the case of TLEP) phases (in whichever order) with an overall duration of 5 to 10 years (up to 20 in the case of TLEP). Its aim would be a precise characterization of the Higgs mechanism:

- (i) A Tera-Z factory at the Z peak for one year;

- (ii) A Mega-W factory at the WW production threshold, for one year;
- (iii) A Higgs factory at an E_{cm} of 240 GeV, for five years providing 10^5 tagged Higgs boson decays;
- (iv) In the case of TLEP, studies with collisions above the t-tbar threshold.

The physics goals and feasibility have been studied in [12], with the following principal conclusions.

Running LEP3 in Higgs factory mode would measure accessible Higgs couplings with a precision up to two times better than at a linear collider with the same E_{CM} energy for the same period of time, because of the larger integrated luminosity and the larger number of detectors collecting data. The precision on the W mass would be reduced to almost 1 MeV.

In combination with a run in Mega-W factory mode, and if the resonant depolarization technique were made operational at 160 GeV, the precision on the W mass would become close to 0.5 MeV, a factor 30 smaller than the current precision. As a reminder, polarization was measured at LEP up to 61 GeV per beam, limited by machine imperfections [13]. A new machine with a better handle on the orbit would increase this limit.

With LEP3 operating as a Tera-Z factory, the precision on all electroweak observables would improve by factors ranging from 25 to 100. A number of outstanding issues with the current LEP1 and SLC measurements would be resolved – as an example here we recall the 2 standard-deviation offset for the number of light neutrino species, currently at 2.984 ± 0.008 , and the 3.2 standard-deviation difference between the values of $\sin^2\theta_{\text{eff}}$ derived from A_{LR} and $A_{\text{FB}}(b)$. It is worth noting that running at the Z pole will be challenging for the experiments, due to the high acquisition rate (25kHz of interesting events). Current acquisition rates, for CMS for instance, are $\sim 1\text{kHz}$, albeit with event sizes about 20 times the sizes expected in LEP3.

LEP3 has a huge potential for precision measurements in the electroweak sector, orders of magnitude better than its pioneering predecessor, LEP, much better than what can be achieved at the LHC, and even better than a linear collider for certain channels. Statistically, the whole of the LEP programme could be repeated at LEP3 in 10 minutes [12].

MAIN DESIGN CONSIDERATIONS

LEP3 is conceived primarily as a Higgs factory with the ability of producing $O(100,000)$ Higgs particles over a three-year period. With the mass of the Higgs around 125GeV, an e+e- collider with centre-of-mass energy (E_{CM}) energy of 240 GeV is sufficient for achieving a Higgs production cross section within 95% of the maximum.

This energy is around 15% higher than the maximum E_{CM} energy achieved at LEP2 (209 GeV). Synchrotron radiation (SR) losses scale with the fourth power of the energy, therefore a 240 GeV machine would consume a factor of two more energy per circulating electron than LEP2. A luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$ would give the above-mentioned desired number of Higgs particles if two interaction points were used (20,000 Higgs particles per year per experiment).

The challenge is whether such a machine can be built: the tunnel exists (27 km, currently housing the LHC), and two general-purpose High Energy Physics experiments are installed and could be re-used (ATLAS and CMS), narrowing the question to whether the machine can achieve such luminosities within a reasonable power budget.

We have limited the total power loss in the ring due to synchrotron radiation to 100 MW (50 MW per beam). This would roughly equate to a wall power consumption of 200 MW (assuming a 50% power efficiency of the RF system). This figure is high, but not abnormally so. Currently CERN has a 200 MW contract with France's electricity provider EdF. Energy consumption figures of the proposed LHeC project are also similar. Projected linear collider power consumptions are up to three times higher (admittedly for higher E_{CM} , which is however not needed for Higgs production).

Limiting the total SR power dissipation for a tunnel with a given bending radius effectively defines the total beam current of the machine (to around 7.2mA with the present assumptions). This also implies that maximum luminosity is achieved by splitting the total current to as few bunches as possible (we are proposing 4 bunches). Our study reveals that a luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$ in several interaction points is possible with such a machine, making the project worth pursuing.

In summary, the starting baseline assumptions and design considerations of LEP3 are as follows:

- Total centre-of-mass energy of 240GeV;
- Re-use of the LHC tunnel and available infrastructures;
- Re-use of the two general-purpose LHC experiments ATLAS and CMS;
- Limiting the total synchrotron radiation losses around the machine to 100MW;
- Maximizing the luminosity delivered to the experiments by designing a low-emittance collider ring with an efficient duty cycle and strong final focusing.

COHABITATION WITH THE CURRENT LHC

Our baseline solution calls for a LEP3 ring situated on top of the current LHC machine, as envisaged in the design brief of the LHC. However, this is not the solution offering the highest performance (for example, a flat ring is preferred, and given the position of the envisaged experiments ATLAS and CMS, this will not be possible with the LEP3 ring on top of the LHC). Nevertheless, the possible options regarding cohabitation with the LHC are as follows:

1. Concurrent operation. Here both machines, the LHC and LEP3, could operate concurrently on a fill-by-fill basis and LEP3 would operate with the main LHC magnets filled with liquid Helium. This mode of operation is similar to the mode of operation needed for LHeC. It is the most challenging option in all respects, but is unnecessary for the physics goals of LEP3.
2. Alternating operation. Here both machines would be installed in the tunnel, with only one operating on a year-to-year or long-shutdown-to-long-shutdown basis. During LEP3 operation, the LHC magnets will not be filled with liquid Helium. This is our baseline design. Some compromises in the lattice design may be necessary to avoid interference with infrastructure components of the LHC, and a method of suspension of the LEP3 accelerator should be designed. This layout would be similar to the layout envisaged by the LHeC design study, from which we have borrowed many elements including the accelerator lattice design. No showstoppers have been found to the LHeC proposal (see section 7.8 in [14]). A possible advantage of this mode of operation might be that part of the installation could be made during shutdowns between LHC operation, decreasing the eventual installation period of LEP3.
3. Single operation. Here LEP3 would be installed after uninstalling the LHC, and could be followed by installation of higher-field magnets for High-Energy LHC operation. The disadvantage of this mode of operation is that one cannot revert to LHC operation after LEP3 (but has to continue with HE-LHC, if desired, instead). There are a series of advantages, however: much simpler logistics, a no-compromise LEP3 lattice, a flat main ring, etc., all of them offering increased performance and lower costs.

Option 1 is undesirable for LEP3, but it will be up to the community to decide which mode of co-habitation with the LHC (2 or 3) is preferable.

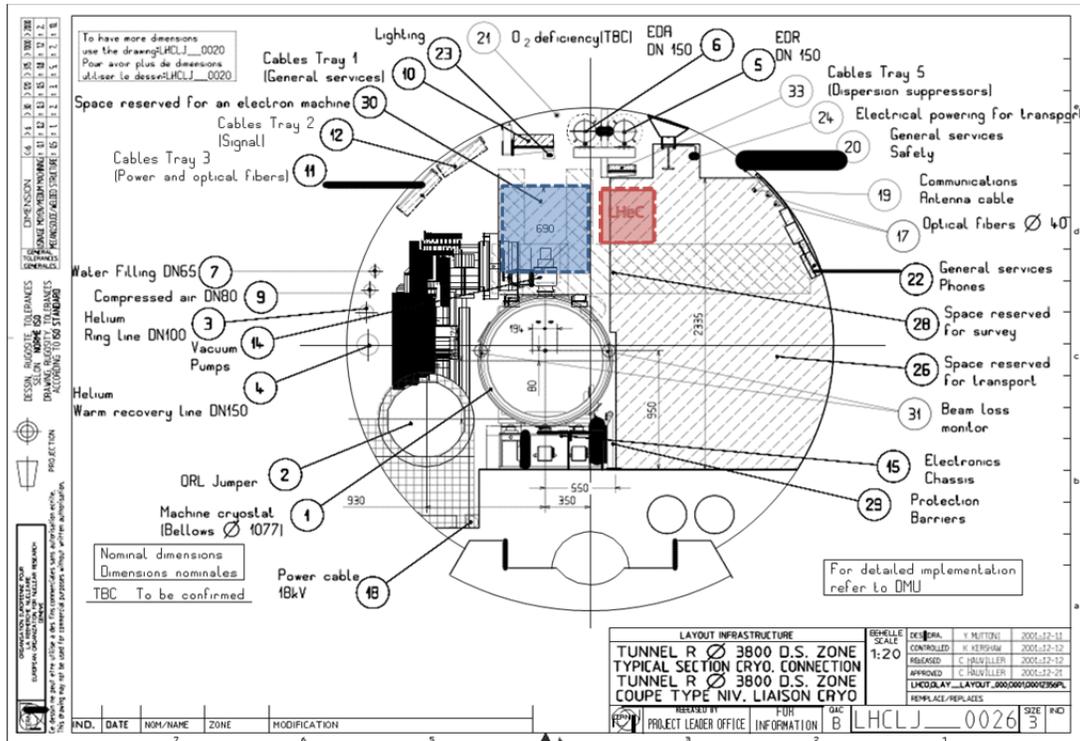


Figure 1: A typical cross section of the LHC tunnel at a cryogenic connection representing the most stringent regular space restriction in the arcs (40 cm every approx. 50 m). In shaded blue, the area reserved for a future e^+e^- collider. In red, the space envisaged for the LHeC electron ring.

ACCELERATOR PARAMETERS

As already emphasized, the primary choice of location for LEP3 is in the LHC tunnel. Advantages are the existence of the tunnel with the associated infrastructure, including cryogenics, and the existence of high-performance detectors, like ATLAS and CMS. In this option, one would install the two compact LEP3 rings on top of the LHC, using light-weight

magnets, similar to the proposed LHeC ring-ring collider [14]. *Figure 2* shows a schematic view of the LEP3 double ring. There is a low-emittance collider ring operating at a constant 120 GeV and a second accelerator ring ramping from injection energy to 120 GeV every few minutes and “topping up” the collider ring. **Table 1** compares parameters for LEP3, DLEP (a new ring with twice the LEP/LHC circumference) and TLEP (in an 80-km tunnel, that can reach higher energies) with those of LEP2 and the LHeC ring design.

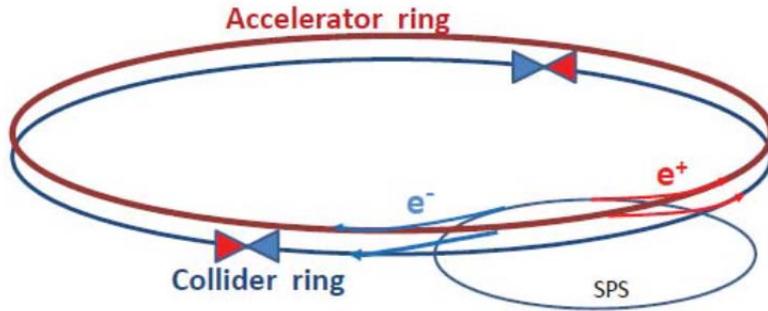


Figure 2: Sketch of the LEP3 double ring [8]: a first ring accelerates electrons and positrons up to the operating energy (120 GeV) and injects them at few-minute intervals into the low-emittance collider ring, which has high-luminosity interaction points.

LEP3 Parameters

We assume the same arc optics as for the LHeC, which provides a horizontal emittance significantly smaller than for LEP, at equal beam energy, and whose optical structure is compatible with the present LHC machine, allowing coexistence with the LHC. The downside of this choice is the dipole filling factor of the LHeC design which is a low 75%. This results in a smaller bending radius than that of LEP (and therefore in a larger SR loss).

Instead of the LHeC 702 MHz RF system we consider ILC-type RF cavities at a frequency of 1.3 GHz, since the latter are known to provide a high gradient and help to reduce the bunch length, thus enabling a smaller β_y^* . (but see also the discussion in the RF section below).

A key parameter is the energy loss per turn: $E_{\text{loss}}[\text{GeV}] = 88.5 \times 10^{-6} (E_b[\text{GeV}])^4 / \rho[\text{m}]$. The bending radius, ρ , for the LHeC is smaller than for LEP (2.6 km compared to 3.1 km), which translates into a higher energy loss than necessary. For 120 GeV beam energy the arc dipole field is 0.153 T, and a compact magnet design as in [14] can be considered.

The critical photon energy of the emitted Synchrotron radiation is 1.4 MeV. The ratio of RF voltage to energy loss per turn is increased with respect to the corresponding value at LEP in order to obtain a larger momentum acceptance. An RF gradient of 20 MV/m is considered, similar to the LHeC linac-ring design and about 2.5 times higher than for LEP. The cryogenic power increases with the square of the gradient. At 20 MV/m RF gradient, the total length of the RF sections at 120 GeV beam energy is about 20% longer than the one for LEP2 at 104.5 GeV, and the cryo power required for the collider ring is expected to be close to the current cryogenic capacity of the LHC.

The unnormalized horizontal emittance is determined by the optics and varies with the square of the beam energy. We scale it from the 60-GeV LHeC value.

The vertical emittance depends on the quality of vertical dispersion and coupling correction. The ultimate limit on the vertical emittance is set by the opening angle effect, and amounts to a negligible value, below 1 fm. We assume the vertical to horizontal emittance ratio to be similar to that for LEP. Beamstrahlung (BS) effects were estimated from analytical formulae [15] [16]. At the collision point the beams should be as flat as possible (large x/y emittance and beta ratios) to minimize energy spread and particle losses resulting from beamstrahlung [17] [18]. The bunch length of LEP3 is smaller than for LEP despite the higher beam energy, due to the smaller momentum compaction factor, the larger RF voltage, and the higher synchrotron frequency. Since LEP3 is far away from the ultimate vertical emittance limit, and since vertical emittance is so important for high luminosity, a study should be initiated to probe the physical limits that can be reached. For instance, a dynamic alignment system for the main magnets could allow the reduction of the horizontal to vertical coupling, reducing vertical emittance.

Similar to the LHeC design, the total RF wall plug power for both beams is taken to be limited to 200 MW. The wall-to-beam energy conversion efficiency is assumed to be 50%. The energy loss per turn then determines the maximum beam current. At 120 GeV beam energy it is 7.2 mA or 4×10^{12} particles per beam. Additional power will be needed for the cryoplants (a total of 10-30 MW depending on the Q_0 value of the cavities [14]) and for the injector/accelerator rings. The total wall plug power of the LEP3 complex would then be between 200 and 300 MW.

If the total charge is distributed over 4 bunches per beam each bunch contains about 10^{12} electrons (or positrons), and the value of the beam-beam tune shift of ~ 0.09 is much less than the maximum beam-beam tune shift reached at KEKB. For comparison, in LEP the threshold bunch population for TMCI (Transverse Mode Coupling Instability) was about 5×10^{11} at the injection energy of 22 GeV. For LEP3, at 120 GeV (with top-up injection, see below), we gain a factor 5.5 in the threshold, which more than cancels a factor $(1.0/0.7)^3 = 2.9$ increase in the magnitude of the transverse wake field (of the SC RF cavities) arising from the change in wake-field strength due to the different RF frequency. We note that only about half of the transverse kick factor in LEP came from the SC RF cavities, so that the actual scaling of the threshold may be more favourable. The TMCI threshold also depends (roughly linearly) on the synchrotron tune. The LEP3 synchrotron tune is about 0.35, while in LEP at injection it was below 0.15. The higher synchrotron tune would bring a further factor of 2 in the TMCI threshold, thus raising the threshold bunch intensity to about 10^{12} particles. Finally, the beta functions in LEP3 at the location of the RF cavities could be designed to be smaller than those in LEP (this is already true for the beta functions in the arcs), which would further push up the instability threshold.

The value of 1 mm considered for β_y^* could be realized by using new higher-gradient larger aperture quadrupoles based on Nb₃Sn (as for HL-LHC), by a judicious choice of the free length from the IP, and possibly by a semilocal chromatic correction scheme. It is close to the value giving the maximum geometric luminosity for a bunch length of 3 mm, taking into account the hourglass effect. With a free length between the IP and the entrance face of the first quadrupole of 4 m, plus a quadrupole length of 4 m, the quadrupole field gradient should be about 17 T/m and an aperture (radius) of 5 cm would correspond to more than $20\sigma_y$, resulting in a reasonable size beam pipe around the interaction points.

At top energy in LEP2, the beam lifetime was dominated by the loss of particles in collisions [19] due to radiative Bhabha scattering with a cross section of 0.215 barn [20]. For a luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ at each of two IPs, we find a LEP3 beam lifetime of 16 minutes — LEP3 would be ‘burning’ the beams to produce physics very efficiently. With a LEP3 energy acceptance, $\delta_{\text{max,RF}}$, of 4%, the additional beam lifetime limit due to beamstrahlung [18] can be larger than 30 minutes, even with beams colliding at two IPs; see *Figure 3*.

In addition to the collider ring operating at constant energy, a second ring (or a recirculating linear accelerator) could be used to ‘top-up’ the collider; see Fig. 1. If the top-up interval is short compared with the beam lifetime this would provide an average luminosity very close to the peak luminosity. For the top-up we need to produce about 4×10^{12} positrons every few minutes, or of order 2×10^{10} positrons per second. For comparison, the LEP injector complex delivered positrons at a rate of order 10^{11} per second [21].

Concerning operation at the Z peak, again we limit the electrical power to 200 MW, with the synchrotron radiation power amounting to about half this value (with $\sim 50\%$ RF generation efficiency). This means that the beam current can increase $(120/45.5)^4 = 50$ times. However, the geometric emittance gets smaller at lower energy as $\sim \text{energy}^2$, which would increase the luminosity as well as the beam-beam tune shift at the lower energy (by a factor 7 and 18, respectively). On the other hand, we only have a factor two margin in the tune shift. For this reason, we need to lower the charge per bunch and further increase the number of bunches. The luminosity scales as beam current times tune shift. The current increases by a factor 50. The tune shift needs to stay the same or can optimistically increase by (at the very most) a factor of 2 (from 0.08 to ~ 0.16). The number of bunches should therefore increase by a factor 50 times 18/2. This brings us to 920 bunches per beam for a luminosity of up to $5 \times 10^{35} / \text{cm}^2 / \text{s}$ at 45.5 GeV beam energy. The two limits are SR power (total current) and maximum beam-beam tune shift, which is taken to be about 0.1 per IP.

Similar scaling arguments can be used for operation at the WW threshold, resulting in about 60 bunches and $7 \times 10^{34} / \text{cm}^2 / \text{s}$ luminosity at a beam energy of 80 GeV.

TLEP parameters

A preliminary parameter list for a 350 GeV E_{CM} collider (above the t-tbar threshold) in an 80-km tunnel has also been developed (see the last column in **Table 1**). The parameters were scaled from the LEP3 numbers of the 27 km ring. Also here the synchrotron radiation power is limited to 50 MW per beam. With regard to beamstrahlung the condition of Telnov [18] is just met, and according to the analytical formula the beam lifetime from beamstrahlung may be between 15 and 30 minutes, to be checked with simulations and not yet fully optimized. This is less than the lifetime due to radiative Bhabha scattering of about 60 minutes (in contrast to the situation at the 240 GeV E_{CM} case where beamstrahlung is not the limiting factor in beam lifetime), but it should be long enough for efficient operation, with top-up injection. The luminosity at 350 GeV E_{CM} is $6.5 \times 10^{33} / \text{cm}^2 / \text{s}$ in each of two IPs. One could get more luminosity by either accepting more synchrotron radiation power, or by colliding in only one IP, or by re-optimizing the bunch parameters, for example by reducing the vertical emittance.

Table 1: Example parameters of LEP3, DLEP (in a 54 km tunnel) and TLEP (in an 80 km tunnel) compared with LEP [19] [22] and the LHeC ring design [14]. Beamstrahlung (BS) effects were estimated from analytical formulae [15] [16].

	LEP2	LHeC	LEP3	DLEP	TLEP
beam energy E_b [GeV]	104.5	60	120	120	175
circumference [km]	26.7	26.7	26.7	53.4	80
beam current [mA]	4	100	7.2	14.4	5.4
#bunches/beam	4	2808	4	60	12
# e^- /beam [10^{12}]	2.3	56	4.0	16.0	9.0
horiz. emit. [nm]	48	5	25	10	20
vert. emit. [nm]	0.25	2.5	0.10	0.05	0.1
bending radius [km]	3.1	2.6	2.6	5.2	9.0
partition number J_e	1.1	1.5	1.5	1.5	1.0
momentum compaction α_c [10^{-5}]	18.5	8.1	8.1	2.0	1.0
SR power/beam [MW]	11	44	50	50	50
β_x^* [m]	1.5	0.18	0.2	0.2	0.2
β_y^* [cm]	5	10	0.1	0.1	0.1
σ_x^* [μm]	270	30	71	45	63
σ_y^* [μm]	3.5	16	0.32	0.22	0.32
hourglass F_{hg}	0.98	0.99	0.67	0.75	0.65
$E_{\text{loss}}^{\text{SR}}/\text{turn}$ [GeV]	3.41	0.44	6.99	3.5	9.3
$V_{\text{RF,tot}}$ [GV]	3.64	0.5	12.0	4.6	12.0
$\delta_{\text{max,RF}}$ [%]	0.77	0.66	4.2	5.0	4.9
ζ_x/IP	0.025	N/A	0.09	0.05	0.05
ζ_y/IP	0.065	N/A	0.08	0.05	0.05
f_s [kHz]	1.6	0.65	3.91	0.91	0.43
E_{acc} [MV/m]	7.5	11.9	20	18	20
eff. RF length [m]	485	42	606	376	600
f_{RF} [MHz]	352	721	1300	1300	700
$\delta_{\text{rms}}^{\text{SR}}$ [%]	0.22	0.12	0.23	0.16	0.22
$\sigma_{z,\text{rms}}^{\text{SR}}$ [cm]	1.61	0.69	0.23	0.17	0.25
L/IP [$10^{32}\text{cm}^{-2}\text{s}^{-1}$]	1.25	N/A	107	142	65
number of IPs	4	1	2	2	2
beam lifetime [min]	360	N/A	16	22	54
Υ_{BS} [10^{-4}]	0.2	0.05	10	8	15
$n_\gamma/\text{collision}$	0.08	0.16	0.60	0.25	0.51
$\Delta E_{\text{col}}^{\text{BS}}$ [MeV]	0.1	0.02	33	12	61
$\Delta E_{\text{rms,col}}^{\text{BS}}$ [MeV]	0.3	0.07	48	26	95

BEAMSTRAHLUNG

Beamstrahlung is an effect coined in [23] as “synchrotron radiation from a particle being deflected by the collective electromagnetic field of the opposing bunch”. The effect of beamstrahlung is to limit the lifetime of the beams, as colliding leptons lose energy that takes them out of the momentum acceptance of the machine.

At LEP3 the effect of beamstrahlung could be very severe for beam lifetimes in case of a momentum acceptance of 2% or lower (**Figure 3** left). In this example the beam lifetime for the LEP3 chosen parameters (β_x^* of 200mm and 100×10^{10} particles per bunch) is a mere 5 minutes. The effect can be eliminated, however, by a large momentum acceptance (of around 3-4% at LEP3 energies) and the tuning of vertical and horizontal emittances and beta functions at the collision points. The effect was simulated using a detailed collision simulator (Guinea-pig) that gave similar results to analytical calculations in [18]. **Figure 3** (right) shows the beam lifetime for a momentum acceptance of 4%.

LEP3 will be a machine where beamstrahlung will be important and therefore some effort should be directed on the one hand at understanding and simulating the phenomenon and on the other on controlling the effects of a 4% momentum acceptance, especially on lattice design.

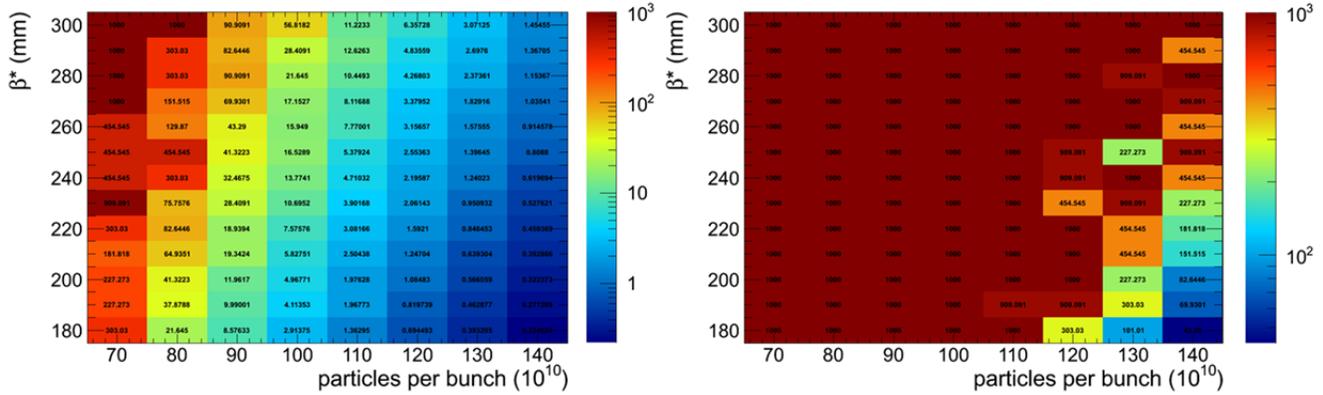


Figure 3: Guinea-Pig simulation of the LEP3 beam lifetime due to beamstrahlung at two IPs in units of seconds (colour) versus bunch population and β_x^* (for $\epsilon_x=20$ nm), for a momentum acceptance of 2% (left) and 4% (right). The proposed number of particles per bunch in LEP3 is 100×10^{10} and the proposed β_x^* 200 mm. Deep red signifies lifetimes of 1000 s or more and it is a safe area for LEP3 operation.

DIPOLE AND QUADRUPOLE MAIN MAGNETS

The best choice for the accelerator main magnets would be conventional iron-dominated electro-magnets. Even for the storage ring constantly at 120 GeV there would be no advantage in using permanent magnets, considering the power consumption of the magnet system compared to the RF. Furthermore, there is an anticipated need to perform an energy scan, implying some tunability in the field.

Per se, the magnets of both rings would not be more challenging than the ones of the LEP era. They would need to be compatible with the emitted synchrotron radiation power and with a satisfactory field homogeneity and reproducibility. However, the one discriminating element here is that these electro-magnets would need to co-exist in the tunnel with the LHC systems installed. This sets very tight constraints, in particular on the size of these magnets. Also, the supports would need to be engineered to provide the required mechanical stability while making the overall installation feasible.

The LEP main bending magnets consisted of 3280 cores, each 5.75 m long [24]. The cores were made of magnetic steel in a concrete matrix, with a stacking ratio of 0.27. The gap was 100 mm, with a flux density ranging from 22 mT (20 GeV) to 110 mT (100 GeV). In the case of the proposed LEP3 machine, the 120 GeV storage ring would have a slighter lower filling ratio of the dipoles in the arcs, resulting in a flux density of 150 mT for the magnets. For the accelerator ring the corresponding magnets would have 25 mT in the gap at injection energy.

Preliminary studies have already been performed for the LHeC accelerator magnets. In the ring-ring layout, such a machine would have similar requirements for the magnets to LEP3, with in particular the same problems of co-existence with the LHC [25]. Flux densities range from 13 mT to 76 mT in a 40 mm gap. The overall cross-section would be, including the coils, around 35 cm wide and 30 cm high. Assuming that such a 40 mm gap is sufficient for LEP3 (for both rings), overall magnet dimensions would be similar to the LHeC design and stacking up two units in a “double decker” configuration, would result in an overall vertical size of 60 cm. Cross-talk effects between the two magnets would need to be properly addressed, possibly with the use of trim coils. It would be challenging to further decrease the size, also in view of mechanical stability requirements. The LHeC magnet length is 5.35m. Longer magnets might be preferable for LEP3.

Regarding the main quadrupoles, compactness seems to be the main requirement. The LHeC ring-ring work can again be used as the baseline design [14]. The current LHeC ring-ring quadrupole design has a 30mm aperture, a 1 m magnetic length, a width and height of 30 cm, and a field gradient at 60 GeV of 8 or 10 T/m (different for QD/QF).

In summary, the LEP3 accelerator magnets and in particular the bending units can benefit from the work done for the LHeC machine. Only a few elements of the LEP design (for example, the single bar conductors used as bus-bars as well) can be used, due to the different compactness targets. The need of having magnets for three synchrotrons (LEP3 booster and main ring, plus existing LHC) in the same tunnel brings very tight constraints on the cross-section of the units and on the overall integration of the systems.

RF CONSIDERATIONS

On the RF front, we can profit from of the enormous progress made in accelerating technology since the days of LEP2. ILC-developed cavities [26] provide a very sound possibility for a LEP3 design.

One-turn losses in LEP3 at top energy with the current lattice taken from LHeC are 7 GeV (a higher filling factor may reduce this figure by 20% or so). However, due to the requirement for large momentum acceptance stemming from the effect of beamstrahlung in LEP3, 12GV of acceleration should be available for the main ring. This figure needs further studies to be established. We have assumed a reasonable 20 MV/m gradient, resulting in 606 m effective RF length. This corresponds to 580 TESLA cavities @ 1.038 m per cavity, or to 73 cryomodules with 8 cavities per module (XFEL type). This in turn corresponds to a total length of 818 m compared to the 864 m of LEP2, i.e. an RF system comparable in size.

A further study that can have an impact on the overall cost of the project is whether the two rings can share the same RF modules, or if a further 7 GV of RF will be needed for the accelerator ring, increasing the total length to about 1200 m.

The next question is the cryogenic power needed for these superconductive cavities: At maximum operating gradient, and assuming the worst-case cavity quality factor Q_0 for the TESLA cavities of 1.0×10^{10} [27], the cryogenic load at 2K is 3 kW per sector, compared with the LHC installed capacity of 2.1 or 2.4 kW per sector. However, this Q_0 value is probably pessimistic, and it is possible that the existing capacity is sufficient.

Regarding the RF power needed, for 100 MW of total beam power at 7.2 mA per beam with 580 cavities, a continuous power of 172 kW per cavity will be required. 1.3 GHz klystrons are currently available for pulsed operation at up to about 150 kW average power [28] [29], and further design work will be required to produce a klystron for continuous wave operation above this power level. One area where current technology is not adequate is in the power couplers, where L-band coupler designs are currently limited to continuous power levels of around 60 kW [30]. The choice of a lower RF frequency such as 700MHz might be considered: this would allow higher klystron average power levels, and the larger physical size of the power couplers and RF distribution components leads to a design which is generally more robust, less sensitive and less challenging.

VACUUM AND BEAM PIPE IN THE PRESENCE OF SYNCHROTRON RADIATION

The vacuum engineering of the beam pipe is critical for a machine where the SR power loss is so high, about 5kW per meter in the arcs. Huge developments have been made on how to handle the SR power for the new generations of SR Facilities (Diamond, Soleil, Alba, MAX IV, etc.). However, the experience gathered at LEP2 is unique and useful for this project. Many lessons were learned – At LEP2, most of the issues were induced by fast changes of the beam orbit which resulted in unexpected high power SR losses which in turn created fast temperature rise and pressure bumps (photon stimulated desorption combined with thermal outgassing). The fast temperature gradient led to leaks due to the differential thermal expansion inside the vacuum interconnections. Also, 50% of the SR power escaping in the tunnel did create severe problems like degradation of organic material (cable insulation) and damage to electronics due to high dose rates and the formation of ozone and nitric acid leading to corrosion problems. Similarly to what was done for LEP, the heat load will be extracted by water circulation. The power being higher, the beampipe cross section being smaller and the lead shielding required being thicker, careful simulations are needed to validate this technical solution.

Regarding the choice of material for the beam pipe, material other than that used for LEP could be considered. At LEP, extruded aluminium was used due to its good thermal conductivity and ability to extrude complex shapes. But this choice also presented a series of limitations: the pressurised hot water for the bake-out was limited to 150°C since the reliability of the vacuum interconnections based on aluminum flanges was a concern at higher temperatures (>150°C); this excluded the use of NEG coatings which have minimum activation temperature of 180°C; corrosion problems mean that materials and brazing fluids should be carefully selected. Stainless steel is an alternative that should be investigated offering a higher resistance to corrosion, reliable vacuum connections and thinner beampipe walls. It also has, however, worse heat conductivity as compared to aluminium, and is more expensive to machine and shape.

As a rough estimate, the critical energy being twice the one of the LEP2, the thickness of the lead shielding required to achieve a similar protection will be twice as thick: 6 mm on top and bottom and 12 mm where the SR is impacting. The magnet being roughly twice smaller, the total weight of lead should remain the same. Regarding vacuum, heavy gasses with a higher ionisation cross section are more harmful than Hydrogen: Argon is 67 times more harmful than Hydrogen. At LEP, the vacuum cleaning took 500 hours since NEG coating technology was not available. This vacuum cleaning will be shortened if NEG coatings (which also offer very low photon stimulated desorption coefficients) are used as baseline.

In conclusion, the LEP3 beam pipe, shielding and heat extraction should be part of an integrated design, and the wealth of information gathered at LEP2 should be of great help.

FINAL FOCUSING

The requirements for LEP3 regarding the final focusing elements are mainly the compact design and compatibility with operation a few meters from the IP and inside a particle detector. The field strength needed is of the order of 20T/m. This is a modest field gradient compared to CLIC proposals (which are a factor of 20 higher). The aperture requirement is 10cm. This leaves the option of superconducting, conventional iron electromagnetic (EM), permanent magnet (PM) or hybrid (PM/EM) as the technology choice.

The superconducting option (with magnetic field strength and quality dominated by the very precise coils winding and positioning) is a well-known and mastered technology, being widely adopted for the LHC magnets and also proposed for the HL-LHC upgrade.

A conventional iron-dominated electromagnetic design it is probably not the most appropriate choice due to the weight and the dimensions of the magnets and the fact that they should be placed inside the Detectors ($L^* \sim 4$ m).

The hybrid PM/EM solution could be very interesting due to:

- the compactness and lightness of the magnets (so minimizing the solid angle subtracted to the Detector volume)
- the limited need of service systems and connections (powering, water and/or cryogenic cooling)
- the absence of cryostats and consequently of thermal contractions, an aspect that simplifies the precise alignment of the quadrupoles, with a direct strong impact on the achievable luminosity.

In this area there are recent R&D activities at CERN for the LINAC4 and CLIC projects. As an example, **Figure 4** (left) shows PM Quadrupole prototype built for LINAC4 project. Its inner magnet bore is 45 mm and its Nominal Gradient 16 T/m. This magnet is not remotely tunable, but it is very compact and the field quality would be appropriate for use in a collider like LEP3.

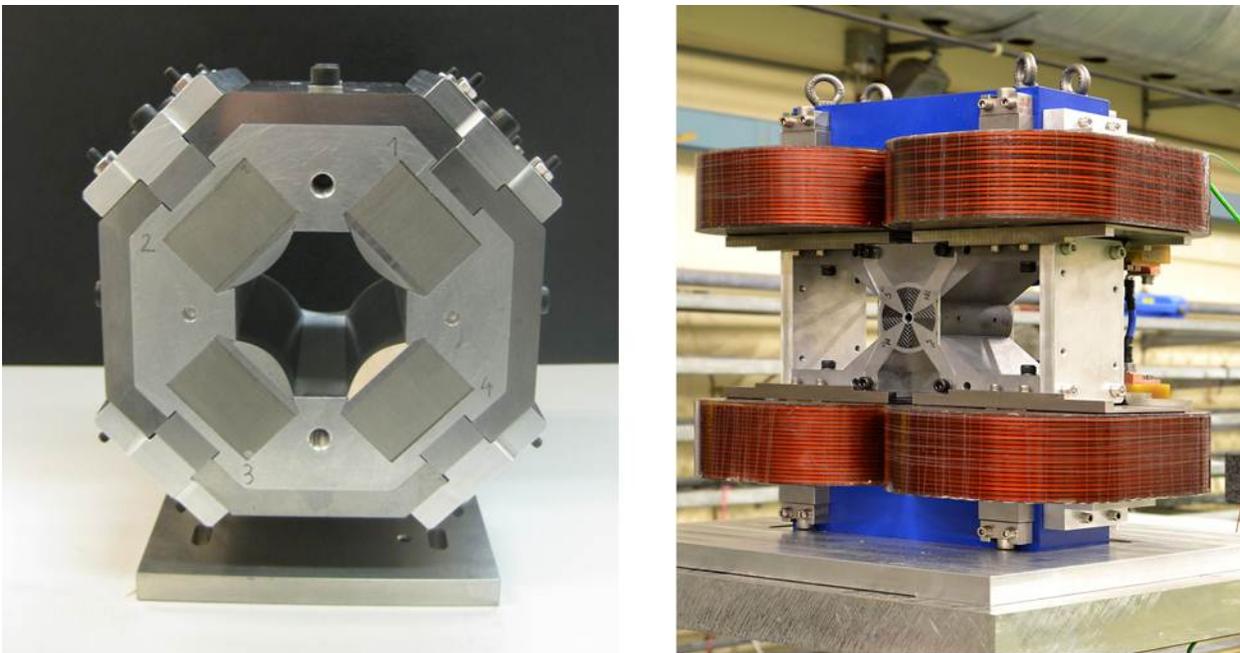


Figure 4: LEFT: Prototype of a Permanent Magnet Quadrupole developed at CERN for the LINAC4 Project. RIGHT: Short prototype of a Tunable Hybrid Final Focus quadrupole built in the framework of CLIC R&D.

Stronger gradients and large remote tunability are possible if one introduces in the design EM coils and with the use of high saturation materials like Permendur.

Figure 4 (right) shows another example, a Tunable Hybrid Final Focus quadrupole developed in the framework of CLIC R&D. The inner magnet bore is 8.12 mm and the maximum gradient is 515 T/m. Tunability is about 70%. Very good field quality was achieved mainly due to the choice of producing the most critical components using the technique of Electrical Discharge Machining EDM.

If the hybrid option is favoured, a solution like the one presented in **Figure 4** (left) but with higher gradient and with the addition of tuning coils could be studied so that it satisfies the LEP3 requirements and at the same time is as small and

lightweight as possible. A similar design option is investigated for a possible upgrade of the ATF2 Final Focus doublets for KEK in Japan.

INJECTION AND FILLING

The LEP injection apparatus has been dismantled. However, the tunnels linking the SPS and the LHC tunnel are available to be re-used. Therefore, a design similar to the injection scheme used for LEP can be envisaged. An injection energy of around 20 GeV would mean that there will be a factor 6 between injection and top energy. The LEP injector complex was able to provide $O(10^{11})$ electrons/positrons per second. LEP3 would require 4×10^{12} electrons/positrons every 16 minutes (or 1000 seconds). This is, therefore, not a very challenging requirement for the injection system that needs to be designed for LEP3.

The nominal ramp rate of LEP was 500 MeV/s [31] (although 125 MeV/s was mostly used). At the same speed, acceleration to 120 GeV would take less than 4 minutes. Roughly constant luminosity and beam currents will be realized through a top-up injection scheme as used at KEKB and PEP-II. With an injector cycle period of, for example, 2 minutes and 16-minute beam lifetime in the collider ring, about 7% of the total bunch intensity needs to re-injected on each cycle. As done at PEP-II the sensitive parts of the detectors probably need to be gated to be blind during injection for a few tens of turns, of the order of the transverse radiation damping time.

MODIFICATIONS TO EXPERIMENTS AND PERFORMANCE

A recent study of the CMS experiment concludes that CMS performance in LEP3 would be similar to the performance of a dedicated linear collider detector [12]. ATLAS is expected to show similar performance, although no dedicated study has been performed yet.

Two integration issues merit closer investigation: the first is the presence of a final focusing quadrupole inside the detector. The first set of parameters for this quadrupole are that it needs a modest 19T/m gradient, it has a length of 4 m and needs to be placed 4m from the IP. Integration issues do not seem extremely challenging with such a device and a possible positioning of such a device inside CMS is shown in *Figure 5*.

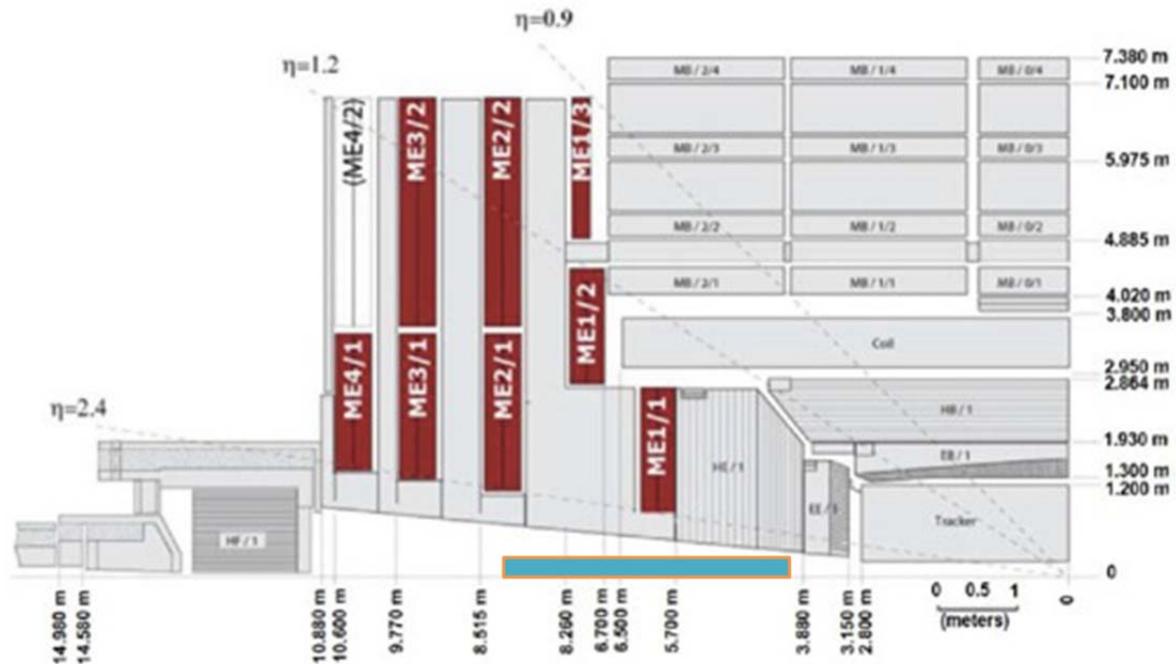


Figure 5: Longitudinal cut of the CMS detector. The final focusing quadrupole is seen in blue 4 m from the IP. Its length is 4m, its radius is 30 cm and the radius of the beam pipe is 5cm.

The second issue is the way that the accelerator beam will pass through or by-pass the detector. A bypass has no integration issues for the detector, but is the more expensive option. A pass-through can be integrated in two ways: the first would be using a separate beampipe that would cross the detector some distance from the main beam pipe (the distance of the two beampipes in the arcs is around 30cm). The second would be to use a common beam pipe for both beams close to the IP, with the accelerator beam coming at a small angle with respect to the horizontal or vertical planes. Both of these solutions have important integration issues that should be looked at carefully to see if any of them is feasible.

In conclusion, CMS can be an excellent e^+e^- detector with a performance for Higgs physics comparable to linear collider detectors. Regarding integration issues, a more comprehensive study should take place.

TWO RINGS VERSUS A ONE-RING DESIGN

The baseline for the LEP3 accelerator is a double ring design due to a manifold of reasons: first, a ring kept constantly at the same energy will always have superior performance to a ring that is ramped. Secondly, the average luminosity of such a machine is kept very close to the maximum luminosity, something especially important in a machine where the beam lifetime is short (16 mins with two IPs) compared to the expected duty cycle of such an accelerator.

On the other hand, a one-ring design has the edge on cost and avoids integration problems or expensive bypasses of the accelerator beams around the experiments.

To be able to calculate exactly how much performance the second ring buys us, we need to make assumptions about the duty cycle of such an accelerator. For LEP2, physics-to-physics times were reduced to a bit less than an hour [32], ramping from injection energy to top energy taking around 13 mins at 125MeV/s acceleration. If LEP3 could manage half this time, i.e. 30 mins, from the duty cycle alone, the average luminosity would be a factor of 0.23 of the peak luminosity (assuming 16 minute beam lifetimes)

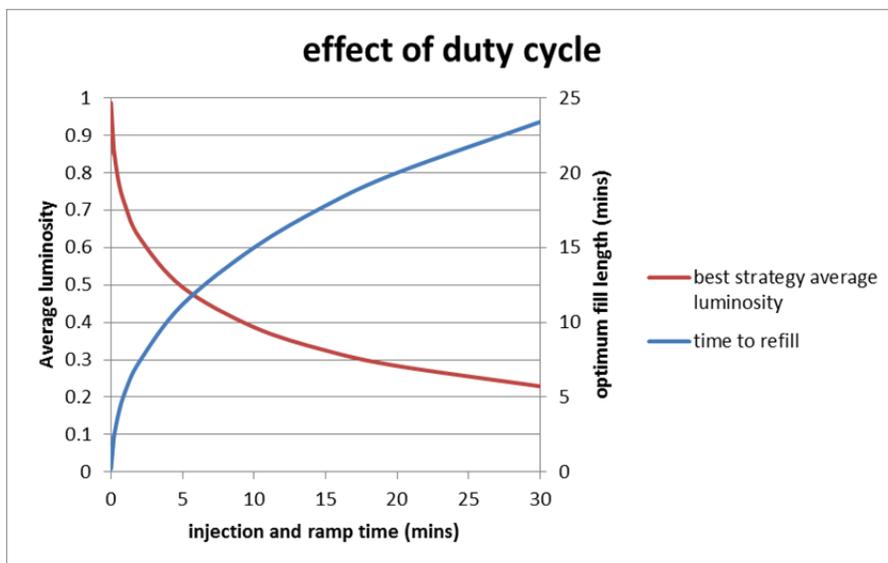


Figure 6: A toy simulation of the effect of the duty cycle to the average luminosity (in red, the best strategy average luminosity, in blue the best strategy time in a fill to refill). Horizontal axis is the time needed for a refill, during which no collisions take place. A two-ring approach has virtually zero refill time. If the time needed to refill is 30 mins, average luminosity is decreased by a factor 4.

Figure 6 shows the effect of different duty cycles on the average luminosity of the machine, assuming no luminosity levelling and with a luminosity lifetime of 16 minutes. If the refill time is milliseconds, then one should refill continuously, and the average luminosity is 1. Refilling every minute one loses some 5% of this theoretical maximum value. This is the case with a two-ring design. On the other hand, if filling takes 30 minutes, then the best strategy is to refill 23 minutes into the fill, achieving an average luminosity which is 23% of the maximum. To be able to approach to within 80% of the luminosity of the two ring design, one needs to be able to fill in 30 seconds, and needs to do so every 4 minutes.

ALTERNATIVE COLLIDERS

LEP3 in the LHC tunnel is not the only possible collider to be used as a Higgs factory, if the cost of excavation of a new tunnel can be contemplated. We here mention other possible circular colliders, existing or proposed, in the Geneva region or elsewhere.

The UNK ring in Russia near Moscow still exists. It is a large bore tunnel, but its circumference is 20 km, inferior to that of LEP3.

A project similar to LEP3, called SuperTRISTAN, has recently been proposed in Japan [33]. This would be a 40 km or a 60 km tunnel in the vicinity of KEK in Japan with a luminosity similar to the one of LEP3. In the very rough cost estimate in [33] more than half of the cost of the project would be for the tunnel and the detectors.

Another possibility, which we call ‘DLEP’, is to build a new larger tunnel, e.g. of twice the LEP circumference, which could later be used to accommodate a High-Energy LHC with 40 TeV centre-of-mass energy. Rings with circumferences up to 50 km were considered during the LEP design in the 1970s with part of the tunnel located in the rocks of the Jura, 800-900 m under the crest [34]. Recent studies actually disfavour a 54-km ring in the Geneva region in favour of a larger 80-km or a smaller 46-km one for reasons that have to do with the morphology of the crust in the Geneva region [35]. Nevertheless our studies show that by relaxing a lot of the parameters of LEP3 (SR power per unit length, beamstrahlung, beam-beam tune shift) we still end up with a machine achieving luminosities higher than $10^{34} \text{ cm}^2\text{s}^{-1}$ in each of two IPs, which outperforms a linear collider. Obviously pushing the parameters higher would result in even better performance.

The largest tunnel considered is an 80 km tunnel that we have labelled TLEP. Such a tunnel could be constructed in a number of sites around the world (CERN, Fermilab, KEK, etc.). A newly commissioned study for an 80km tunnel in the Geneva region has published its preliminary findings in [35]. Planning and cost assessments will be available in separate report at the end of August 2012. An 80 km tunnel paves the way for a 350 GeV E_{cm} machine above the top-quark pair-production threshold and its associated precision measurements. Such a tunnel could be used for a very-high-energy proton accelerator as well.

INDICATION OF TIMESCALE AND COSTS

The concept of LEP3 is sufficiently interesting to deserve a dedicated study that we can see can take place in three steps:

1. A first year dedicated to the conceptual study in order to find any show stopper, scope out the specific physics and experimental environment offered by the machine, and identify the most critical R&D issues and installation scenarios.
2. In a second phase (about 2 years) a design study should be undertaken, in parallel with a first set of R&D on the most critical items. This phase would be concluded with a Conceptual Design Report.
3. Finally, if the case for the machine is still present, the preparation of a Technical Design Report including the installation plan would be prepared.

We envisage that these three phases need 5-7 years to be completed.

Regarding the possible length of the installation period, it is interesting to recall the installation time needed for LEP. All LEP magnets were manufactured and were ready to be installed at the end of 1987. On 8 February 1988, the excavation of the tunnel was completed and the first beam circulated on 14 July 1989. Thus LEP took 18 months to install.

Depending on the need for Z pole running, the RF system could be staged over a couple of years. If it is decided not to build experiment bypasses for the accelerator ring, as in the baseline design, no substantial civil engineering works would be needed.

Regarding how LEP3 fits to the LHC schedule, a possible time for installation would be LS4 (around 2025), the more aggressive possibility being LS3. Note that this timescale fits well with the possibility to continue with a high-energy proton collider (HE-LHC) after LEP3, as the high field magnets needed cannot be ready before around 2032-2035 (for a medium-field magnet design (15Tesla) the aggressive timescale is 2030) [36].

A go/no-go decision on LEP3 can only be taken after adequate data have been taken at an energy of 13-14 TeV at the LHC, since then the physics landscape would be more clear. This effectively means a decision to go ahead during LS2 in around 2018.

Any figures of costs, even preliminary, would be well beyond the scope of this paper. However, reference [33] indicates that the cost of a LEP3-like machine is shared more or less equally between the cost of a new tunnel and associated infrastructure, and the cost of the accelerator proper. The baseline LEP3 baseline design is more economical, as it re-uses the LHC tunnel and infrastructure, as well as the two LHC general-purpose experiments.

REQUIRED R&D AND SYNERGIES

Storage-ring colliders represent a well-established robust technology. Nevertheless, LEP3 is not an easy machine, but must master a number of challenges. Novel features of LEP3 are the about 15% higher energy than LEP2; top-up injection, requiring a dedicated accelerator ring to sustain near-constant luminosity; ultralow vertical β^* (which is still 3-4 times larger than the design β^* value for the two Super B factories); heating and stability issues for short bunches with high bunch charge; and operation in a regime of significant beamstrahlung [17] [18].

The LEP3 machine parameters need to be further optimized. One important point to be addressed is the 3-D integration in the LHC tunnel and possible cohabitation with HL-LHC and LHeC. A further, related issue is the RF integration. Other important R&D items for LEP3 include: (1) beam dynamics studies and optics design for the collider ring; HOM heating with large bunch currents and very small bunch lengths (0.3 cm), vertical emittance tuning, single-bunch charge limits, longitudinal effects associated with a Q_s of 0.35, low beta insertion with large momentum acceptance, parameter optimization, beam-beam effects including beamstrahlung, and the top-up scheme; (2) optics design and beam dynamics for the accelerator ring, and its ramping speed; (3) the design and prototyping of a collider-ring dipole magnet, an accelerator-ring dipole magnet, and a low-beta quadrupole; (4) 100 MW synchrotron radiation effects: damage considerations, energy consumption, irradiation effects on LHC and LEP3 equipment, associated shielding and cooling; (5) SRF and cryogenics design and prototyping (possibly in synergy with SPL and LHeC), (6) determining the optimum RF gradient as a compromise between cryo power and space, and the optimum RF frequency with regard to impedance, RF efficiency and bunch length; (7) engineering study of alternative new 53-km and 80-km tunnels for DLEP and TLEP (and HE-LHC); (8) cost and performance comparison for the proposed double ring and for a single combined ring; (9) design study of the LEP3 injector complex, including a positron source, and a polarized electron source; (10) study of a dual use ring for LEP3 and LHeC; (11) machine-detector interface, e.g. the integration of warm low-beta quadrupoles inside the ATLAS and CMS detectors; (12) detector performance and upgrade studies for LEP3, suitability of the existing LHC detectors (or the desirability of new ones) for LEP3 physics – this is well under way – and additional equipment needed (low beta insertions and luminosity monitors); and (13) LEP3 physics studies (also well under way) [12].

Development of arc magnets and 3-D integration can profit from synergies with the LHeC. Also part of the SRF development could proceed together with similar activities for HP-SPL and LHeC. LEP3 RF cavities and RF power sources could be also used for an ERL-based LHeC (or vice versa).

SUMMARY

The parameter list of Table 1 allows us to draw several encouraging conclusions: It is possible to envisage an electron-positron collider in the LEP/LHC tunnel with reasonable parameters operating at 120 GeV per beam with a peak luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in each of up to four interaction points leading to integrated luminosities of $100 \text{ fb}^{-1}/\text{yr}$ per experiment, while keeping the total synchrotron radiation power loss below 100 MW. The beam lifetime is short (16 minutes for 2 interaction points). A good efficiency calls for a machine with two rings: the storage ring on one hand and an independent accelerator for the positrons and electrons that tops up the storage ring with a sufficient repetition rate to level the luminosity close to the peak value. An $e^+e^- \rightarrow HZ$ cross section of 200 fb yields 2×10^4 events per year and per experiment, and the accelerator can operate as a Tera-Z and a Mega-W factory, allowing measurements of the electroweak sector of unprecedented accuracy.

REFERENCES

- [1] B. Richter, "Very high energy electron positron colliding beams for the study of weak interactions," *Nucl. Instr. Meth.* 136, pp. 47-60, 1976.
- [2] M. Tigner, *Nuovo Cimento*, vol. 37, p. 1228, 1965.
- [3] U. Amaldi, *Phys. Lett.* 61B, p. 313, 1976.
- [4] J. E. Augustin et al., "Proceedings of the Workshop on Possibilities and Limitations of Accelerators and Detectors," *FNAL*, p. 87, 1979.
- [5] G. Dugan et al., "Workshop on an e+e- in the VLC tunnel," in *Fermilab-Conf-01/107-T*, Illinois Institute of technology, Chicago IL, March 9-11 2001.
- [6] ATLAS collaboration, "Observation of an Excess of Events in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC," *ATLAS note ATLAS-CONF-2012-093*, 2012.
- [7] CMS collaboration, "Observation of a new boson with mass near 125 GeV," *CMS physics analysis summary CMS-PAS-HIG-12-020*, 2012.
- [8] A. Blondel and F. Zimmermann, "A High Luminosity e+e- Collider in the LHC tunnel to study the Higgs Boson," *arXiv:1112.2518v2*, 24.12.2011.

- [9] A. Blondel et al., “LEP3: A High Luminosity e^+e^- Collider in the LHC Tunnel to Study the Higgs Boson,” in *IPAC-2012-TUPPR078*, New Orleans, USA, 2012.
- [10] M. Peskin, “Comparison of LHC and ILC Capabilities for Higgs Boson Coupling Measurements,” *arXiv:1207.2516v1*.
- [11] J. E. Brau et al., “The Physics Case for an e^+e^+ Linear Collider,” *Contribution to the European Strategy, July 2012, and references therein.*
- [12] P. Azzi et al., “Prospective Studies for LEP3 with the CMS detector,” *CMS NOTE 2012/003*.
- [13] LEP energy working group: R. Assmann et al., “Calibration of centre-of-mass energies at LEP 2 for a precise measurement of the W boson mass,” *Eur.Phys.J.*, vol. C39, pp. 253-292, 2005.
- [14] O. Bruening et al., “A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector,” *arXiv:1206.2913v1*.
- [15] K. Yokoya, P. Chen, “CERN US PAS 1990,” *Lect.Notes Phys. 400*, pp. 415-445, 1992.
- [16] K. Yokoya, *Nucl.Instrum.Meth. A251*, p. 1, 1986.
- [17] K. Yokoya, “Scaling of High-Energy e^+e^- Ring Colliders,” in *KEK Accelerator Seminar*, 15.3.2012.
- [18] V. Telnov, “Restriction on the energy and luminosity of e^+e^- storage rings due to beamstrahlung,” *arXiv:1203.6563v*, 29 March 2012.
- [19] R. Assmann, “LEP Operation and Performance with Electron-Positron Collisions at 209 GeV,” in *11th Workshop of the LHC*, Chamonix, France, 15 - 19 January 2001.
- [20] H. Burkhardt, “Beam Lifetime and Beam Tails in LEP,” CERN-SL-99-061-AP, 1999.
- [21] R. Bossart et al, “The LEP Injector Linac,” CERN-PS-90-56-LP, 1990.
- [22] A. Butterworth et al, “The LEP2 superconducting RF system,” *NIMA*, vol. 587, no. 2-3, p. 151, 2008.
- [23] J. E. Augustin et al, “Limitations on Performance of e^+e^- Storage rings and Linear Colliding Beam Systems at High Energy,” in *1st Workshop on Possibilities and Limitations of Accelerators and Detectors eConf C781015, (1978) 009*, 15-21 Oct 1978.
- [24] M. Giesch and J.P. Gourber, “The bending magnet system of LEP,” in *MT-11*, 28 Aug. - 1 Sep. 1989.
- [25] S. Russenschuck, “Challenges for the Magnet System of LHeC,” in *IPAC 2012*, May 2012.
- [26] H. Hayano, “Review of SRF cavities for ILC, XFEL and ERL applications,” in *IPAC10*, Tsukuba, Japan, 2010.
- [27] “ILC Reference Design Report Vol. III,” pp. III-159, 2007.
- [28] A. Balkcum et al, “Design and operation of a high power L-band multiple beam klystron,” in *PAC 2005*, Knoxville, Tennessee, 2005.
- [29] Thales Electron Devices, Velizy, France, “TH 2104 L-band klystrons,” [Online]. Available: www.thalesgroup.com/Portfolio/Documents/Klystron_TH_2104.
- [30] M. Liepe, “Experience with the Cornell ERL Injector SRF Cryomodule during High Beam Current Operation,” in *ERL 2011*, Tsukuba, Ibaraki, Japan, 2011.
- [31] P. Collier and G. Roy, “Removal of the LEP Ramp Rate Limitation,” *SL-MD Note 195*, 1995.
- [32] D. Brandt et al., “Accelerator physics at LEP,” *Rep. Prog. Phys.*, vol. 63, p. 939, 2000.
- [33] K. Oide, “SuperTRISTAN - A possibility of ring collider for Higgs factory,” *KEK seminar*, 13 February 2012.
- [34] H. Schopper, *The Lord of the Collider Rings at CERN 1980-2000*, Springer-Verlag Berlin Heidelberg, 2009.
- [35] J. Osborne et al, “Pre-feasibility study for an 80 km tunnel projet at CERN,” CERN EDMS Nr: 1233485.
- [36] O. Bruening et al., “High Energy LHC, document prepared for teh European HEP strategy update,” *CERN-ATS-2012-237*.