LEP3: A HIGH LUMINOSITY e^+e^- COLLIDER IN THE LHC TUNNEL TO STUDY THE HIGGS BOSON

A.P. Blondel, U. Geneva, Switzerland; F. Zimmermann, CERN, Geneva, Switzerland;
M. Koratzinos, Geneva, Switzerland; M. Zanetti, MIT, Cambridge, Massachusetts, USA

Abstract

Recent indications from the LHC suggest that the Higgs boson might be light, within the mass range 115-130 GeV. Such object could be studied at an e^+e^- collider with about 240-GeV centre-of-mass energy. A corresponding Higgs factory – 'LEP3' – could be installed in the LHC tunnel, reducing its cost and also allowing for a second life of the two LHC general-purpose detectors. We present preliminary accelerator and beam parameters for LEP3 [1] tailored so as to provide a peak luminosity of 10^{34} $\text{cm}^{-2}\text{s}^{-1}$ at each of two experiments, while respecting a number of constraints including beamstrahlung limits. At this luminosity around 20,000 Higgs events per year per experiment could be obtained for a Standard Model Higgs boson with a mass of 115-130 GeV. For the parameters considered the estimated luminosity lifetime is about 16 minutes, and the synchrotron radiation losses are 50 MW per beam. High operational efficiency requires two rings: a low emittance collider storage ring operating at constant energy, and a separate accelerator to top up the colliding beams every few minutes. The alternative of a larger ring collider installed in a new, bigger tunnel will also be discussed. The LEP3 collider could as well operate on the Z resonance, where it would achieve luminosities above 10^{35} $\text{cm}^{-2}\text{s}^{-1}$.

ACCELERATOR OPTIONS & OVERVIEW

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 [2]. Another possibility, called '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 c.m. 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 [3]. A project similar to LEP3, called SuperTRISTAN has recently been proposed in Japan [4]. Figure 1 shows a schematic of the LEP3 double ring. Table 1 compares parameters for LEP3 and DLEP with those of LEP2 and the LHeC ring design.

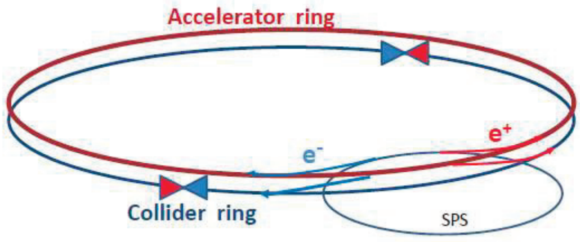

Figure 1: Sketch of LEP3 double ring [1]: a first ring accelerates electrons and positrons up to operating energy (120 GeV) and injects them at a few minutes interval into the low-emittance collider ring, which includes two high luminosity (10^{34} $\text{cm}^{-2}\text{s}^{-1}$) interaction points.

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. 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. A key parameter is the energy loss / turn: $E_{\text{loss}}[\text{GeV}]=88.5\times10^{-6}(E_b[\text{GeV}])^4/\rho[\text{m}]$. The bending radius, ρ, for the LHeC is smaller than for LEP, which translates into a higher energy loss (than necessary). For 120 GeV beam energy the arc dipole field is 0.153 T. A compact magnet design as in [2] can be considered. The critical photon energy 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 cryo 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 less than half the amount used for 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. We assume the vertical to horizontal emittance ratio to be similar to the one for LEP. The ultimate limit on the vertical emittance is set by the opening angle effect, and amounts to a negligible value, below 1 fm. Beamstrahlung (BS) effects were estimated from analytical formulae [7, 8]. At the collision point the beams should be as flat as possible (large *x/y* emittance

ISBN 978-3-95450-115-1

Table 1: Example parameters of LEP3 and DLEP compared with LEP [5, 6] and LHeC ring design [2]. Beamstrahlung (BS) effects were estimated from analytical formulae [7, 8].

	LEP2	LHeC	LEP3	DLEP
b. energy E_b [GeV]	104.5	60	120	120
circumf. [km]	26.7	26.7	26.7	53.4
beam current [mA]	4	100	7.2	14.4
#bunches/beam	4	2808	4	60
#$e-$/beam [10^{12}]	2.3	56	4.0	16.0
horiz. emit. [nm]	48	5	25	10
vert. emit. [nm]	0.25	2.5	0.10	0.05
bending rad. [km]	3.1	2.6	2.6	5.2
part. number J_ε	1.1	1.5	1.5	1.5
mom. c. α_c [10^{-5}]	18.5	8.1	8.1	2.0
SR p./beam [MW]	11	44	50	50
β^*_x [m]	1.5	0.18	0.2	0.2
β^*_y [cm]	5	10	0.1	0.1
σ^*_x [μm]	270	30	71	45
σ^*_y [μm]	3.5	16	0.32	0.22
hourglass $F_{\rm hg}$	0.98	0.99	0.67	0.75
$E^{\rm SR}_{\rm loss}$/turn [GeV]	3.41	0.44	6.99	3.5
$V_{\rm RF,tot}$ [GV]	3.64	0.5	12.0	4.6
$\delta_{\rm max,RF}$ [%]	0.77	0.66	4.2	5.0
ξ_x/IP	0.025	N/A	0.09	0.05
ξ_y/IP	0.065	N/A	0.08	0.05
f_s [kHz]	1.6	0.65	3.91	0.91
$E_{\rm acc}$ [MV/m]	7.5	11.9	20	418
eff. RF length [m]	485	42	606	376
$f_{\rm RF}$ [MHz]	352	721	1300	1300
$\delta^{\rm SR}_{\rm rms}$ [%]	0.22	0.12	0.23	0.16
$\sigma^{\rm SR}_{z,\rm rms}$ [cm]	1.61	0.69	0.23	0.17
L/IP[10^{32}cm^{-2}s^{-1}]	1.25	N/A	107	142
number of IPs	4	1	2	2
beam lifetime [min]	360	N/A	16	22
$\Upsilon_{\rm BS}$ [10^{-4}]	0.2	0.05	10	8
n_γ/collision	0.08	0.16	0.60	0.25
$\Delta E^{\rm BS}$/col. [MeV]	0.1	0.02	33	12
$\Delta E^{\rm BS}_{\rm rms}$/col. [MeV]	0.3	0.07	48	26

and beta ratios) to minimize energy spread and particle losses resulting from beamstrahlung [9, 10]. 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. Similar to the LHeC design, the total RF wall plug power per beam 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 [2]) and for the injector/accelerator rings. The total wall plug power of the LEP3 complex would then be between 200 and 300 MW. If we distribute the total charge 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 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 $(1.0/0.7)^3$ 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 above 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 Nb$_3$Sn (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 $20\sigma_y$.

At top energy in LEP2, the beam lifetime was dominated by the loss of particles in collisions [5] due to radiative Bhahba scattering with a cross section of 0.215 barn [11]. For a luminosity of 10^{34} cm^{-2}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, $\delta_{\rm max,RF}$, of 4%, the additional beam lifetime limit due to beamstrahlung [10] can be larger than 30 minutes, even with beams colliding at two IPs; see Fig. 2.

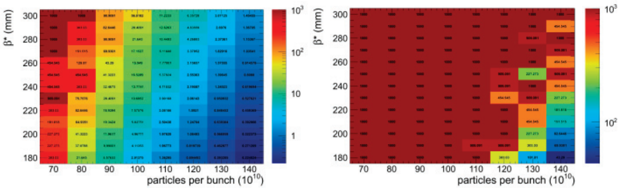

Figure 2: LEP3 beam lifetime due to beamstrahlung at two IPs in units of seconds (color) simulated by Guinea-Pig versus bunch population and β_x^* at ε_x=20 nm, for a momentum acceptance of 2% (left) and 4% (right). Beam lifetimes above 1000 s cannot be resolved due to the finite number of macro-particles used in the simulation.

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 [12].

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 [9, 10].

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 (<0.3cm), 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 tunnel for DLEP (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 and additional equipment needed (low beta insertions and luminosity monitors); and (13) LEP3 physics studies.

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. However, to obtain the short bunch length required, the preferred RF frequency for the LEP3 collider might be the ILC frequency of 1.3 GHz. 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} cm^{-2}s^{-1} in each of two interaction points leading to an integrated luminosity of 100 fb^{-1}/yr, while keeping the total synchrotron radiation power loss below 100 MW. The beam lifetime is short (16 minutes). 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 in each of two experiments, allowing precise measurements of the Higgs Boson mass, cross section and decay modes, even invisible ones. It would also provide more than 10^6 *WW* events per year in each IP.

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ISBN 978-3-95450-115-1