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The Circular Road to a Higgs Factory and Beyond

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Over the past 50 years nearly 30 ring colliders have been built and operated successfully in various laboratories and countries. At the same time, an even larger number of storage-ring light sources with ever smaller transverse emittance have been constructed. Vast experience and highly refined expertise with ring colliders and storage rings have, thereby, been accumulated by the worldwide accelerator community.

For the next 50 years ring colliders are likely to remain the accelerator workhorse at the high-energy frontier, in the form of a next high-energy hadron collider after the LHC and an e^+e^- collider sharing the same tunnel, serving as precision Higgs factories and more.

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1. Circular pp Higgs factories

The LHC is the first Higgs factory. So far it has produced more than 1 million Higgs particles and, in fact, allowed the discovery of this boson. A possible upgrade path of the LHC and two options for future hadron colliders after the LHC are being considered, as summarized in Table 1.

Table 1: The planned/proposed upgrade path of the LHC including two higher-energy successors.

Machine	E_{CM} [TeV]	$\mathscr{L}$ [10^{34} cm^{-2}s^{-1}]	Remarks	Year
LHC	8–14	1	the first Higgs factory	2009 –
HL-LHC	14	5^a	planned, 10× more Higgs	2022–2035
HE-LHC	33	≥ 5	proposed in the LHC tunnel, 6× higher cross section for Higgs self-coupling	2038 – ?
VHE-LHC	84–104	≥ 5	proposed in a new 80–100 km tunnel, 42× higher cross section for H self-coupling	2040 – ?

[a] leveled

The VHE-LHC represents the only available approach for reaching an energy scale of tens of TeV with near state-of-the-art technology. Among other characteristics, the VHE-LHC will be the ultimate Higgs factory, as the cross-section for the Higgs self-coupling will be much higher than for the LHC [1]. Both the HE-LHC and VHE-LHC require a next-generation high-field magnet [2]. Figure 1 shows the result of a pre-feasibility study [3] for an 80 km tunnel in the Geneva region, which was submitted to the 2012 European Strategy Symposium. The 80-km tunnel is close to the Salève mountain and may need $\sim$25 km parallel tunnel for safety reasons. Access shafts on that side would be more than 1000 m long and steep. Recently it is thought that a 100 km tunnel might be better [4]. The 100 km tunnel would pass further away from the Salève, may avoid the aforementioned problems, and could potentially be cheaper.

Machine parameters for the LHC, its luminosity upgrade (HL-LHC), and two possible successors are listed in Table 2. One of the most peculiar features of the VHE-LHC is the — for a proton beam — unprecedentedly short synchrotron radiation damping time of only 20–40 minutes. The corresponding transverse emittance shrinkage would rapidly increase the beam-beam tune shift to unacceptable levels. The planned mitigation technique consists in continuous controlled excitation with longitudinal and transverse “pink noise,” so as to maintain constant beam-beam parameters and a constant bunch length. Operation with a shorter bunch spacing, e.g. 5 ns instead of 25 ns, would allow making better use of the strong damping and obtaining a higher luminosity still.

2. Circular e^+e^- Higgs factories

The discovery of the Higgs boson by LHC in 2012 at 126 GeV has opened up the possibility of a circular e^+e^- Higgs factory [5][1], operating at 240 GeV centre-of-mass (CM). At this energy, only 15% higher than that of LEP2, the Higgs production cross section in e^+e^- collisions is maximum. A number of possible realizations of such a collider have been proposed, starting with “LEP3,”

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[1] A further option is Higgs production in ep (and $\gamma\gamma$) collisions at the “LHeC” [6].

Table 2: Parameters for LHC, HL-LHC, HE-LHC and VHE-LHC. "SR" stands for synchrotron radiation.

Parameter	LHC	HL-LHC	HE-LHC	VHE-LHC	unit
CM Energy	14		33	100	TeV
Circumference	26.7			80(100)	km
Dipole field	8.33		20	20(16)	T
Beam current	0.58	1.12	0.48	0.49	A
IP spot size (H/V)	16 / 7	≥ 7.1	5.2	6.7	μm
Stored beam energy	362	694	701	6610	MJ
SR power / ring	3.6	7.3	96.2	2900	kW
SR heat load in the arc	0.17	0.33	4.35	43.4	W/m/aperture
Energy loss / turn	6.7		201	5857	keV
Critical photon energy	44		575	5474	eV
SR damping time for $\varepsilon_{\|\|}$	12.9		1.03	0.32	h
Peak events / crossing	27	135[a]	147	171	
Peak luminosity	1.0	5.0	≥ 5.0	≥ 5.0	10^{34} cm^{-2}s^{-1}
Beam lifetime due to burn-off	45	15.4	5.7	14.8	h
Optimum luminosity / day	0.5	2.8	1.4	2.1	fb^{-1}

[a] leveled

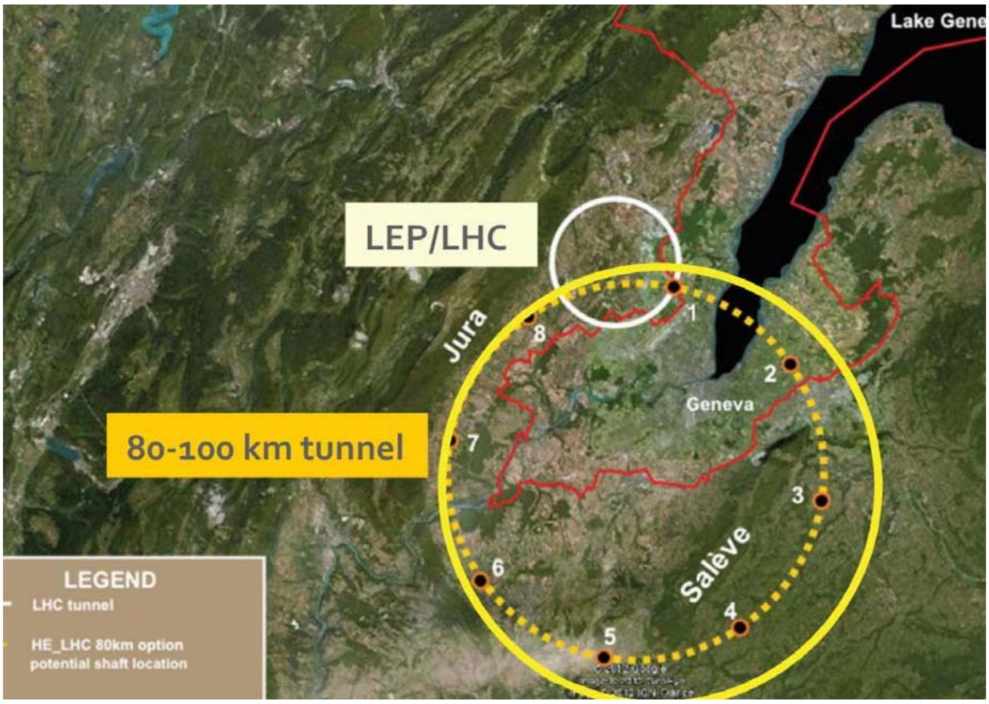

Figure 1: Possible layouts of new 80–100 km tunnels passing through the CERN site [3, 4].

which would be installed in the existing 27-km LHC tunnel. The most versatile version is “TLEP,” an e^+e^- collider sharing a new 80–100 km tunnel with the next-generation 100-TeV hadron collider, VHE-LHC. TLEP would operate up to the $t\bar{t}$ threshold, or, with additional rf cavities, even up to 500 GeV CM, as well as provide an extremely high luminosity at the Z-pole and at the W^+W^- threshold, possibly with polarized beams. TLEP and VHE-LHC enhance each other’s physics cases and maximally exploit a common infrastructure, even more so than LEP and LHC did. TLEP and VHE-LHC will share not only tunnel, cryogenics, etc., but possibly many other components, *e.g.*, injector-ring magnets and physics detectors. With a larger tunnel cross section than LEP, they also offer the prospect of highest-energy highest-luminosity lepton-hadron collisions (“VHE-LHeC”).

TLEP accommodates 4 interaction points (IPs), and achieves 300 times the luminosity of LEP2, thanks to smaller β_y^* and smaller emittances, together with a top-up injection supporting the short beam lifetime at the target luminosity. Proposed machine parameters at various beam energies are listed in Table 3. The beam-beam tune shifts are consistent with LEP experience [7].

Table 3: Parameters for TLEP in a 100 km tunnel. Numbers shown in () for TLEP-t refer to an option with fewer bunches, facilitating the use of a common rf system for both beams, and with larger IP spot size.

Parameter	TLEP-Z	TLEP-W	TLEP-H	TLEP-t	(T-500)	
CM Energy	91	160	240	350	500	TeV
Beam current	1440	154	29.8	6.7	1.6	mA
Bunches / beam	7500	3200	167	160 (20)	10	
Particles / bunch	4.0	1.0	3.7	0.88 (7.0)	3.3	10^{11}
Emittances (H/V)	29 / 0.06	3 / 0.017	7.5 / 0.015	2 / 0.002	4 / 0.004	nm
β^* (H/V)	500 / 1	200 / 1	500 / 1	1000 / 1	1000 / 1	mm
IP spot size (H/V)	121 / 0.25	26 / 0.13	61 / 0.12	45 / 0.045 (126 / 0.13)	63 / 0.063	μm
Bunch length[a]	2.93	1.98	2.11	0.77 (1.95)	1.81	mm
SR loss / turn	0.03	0.3	1.7	7.5	31.4	GeV
Rf voltage	2	2	6	12	35	GV
Beam-beam $\xi_{x,y}$ / IP	0.068	0.086	0.094	0.057	0.075	
Lum. / IP	59	16	5	1.3 (1.0)	0.5	10^{34} cm^{-2}s^{-1}
Beam lifetime, due to rad. Bhabha	99	38	24	21 (26)	13	min
Beam lifetime, due to beamstrahlung[b]	$> 10^{25}$	$> 10^6$	38	14 (2)	0.3	min

[a] includes the multi-turn buildup by beamstrahlung

[b] assuming $\eta = 2.0\%$ acceptance

TLEP is conceived as a double-ring collider covering a wide range of collision energies. Its arc optics consists of FODO cells, the period length of which is varied with energy to provide appropriate emittances, by turning on/off several quadrupoles per cell. Each 1-m long rf cavity must transmit about 200 kW of rf power to the beam, independently of beam energy. In order to provide maximum rf voltage at highest energies, the rf cavities can be shared between the two beams for a sufficiently low number of bunches, which is the case for TLEP-t. This sharing requires a transverse movement of the cavities and associated beam lines by some 10 cm and the introduction of separator magnets.

Any textbook may say that an electron storage ring is fundamentally limited by the synchrotron radiation in the arc. Although this is still true for TLEP, the actual value of the radiated power per unit arc length is only about 9 W/cm for TLEP-Z, -H, -t, which is much smaller than the corresponding numbers for PEP-II (102 W/cm) or SPEAR3 (92 W/cm) [8]. One may worry about the high energy component of the radiated photons, but the photon spectrum of TLEP-t (E = 175 GeV, ρ = 9–11 km) is still lower than in the original LEP design (E = 130 GeV, ρ = 3.1 km) [9].

TLEP and LEP3 assume a top-up operation during physics running, as already routinely used at KEKB and PEP-II. For TLEP the top-up injection at the collision energy is accomplished by a booster synchrotron, which is common for e^+ and e^-. A typical filling cycle would entail a new injection, *e.g.*, every 20 sec per ring, assuming a synchrotron which has the same ramping speed as the SPS, *i.e.*, accelerating from 20 to 120 GeV in 1.6 sec. Such injection scheme can keep the variation of the stored current to within ±1% for a beam lifetime of 15 minutes.

The two dominant processes determining the beam lifetime of TLEP are listed in Table 3: One is the radiative Bhabha scattering in the collision, which is simply proportional to the luminosity and thus unavoidable. Another is the beamstrahlung at the collision, which at each collision causes a large momentum deviation for a few beam particles [10]. The latter can be mitigated by making the spot at the IP as flat as possible, by enlarging the momentum acceptance (dynamic aperture) of the ring, and by a quick refill using the top-up operation. The momentum acceptance is limited by the chromatic correction of the interaction region. A preliminary study has demonstrated the feasibility of an interaction region optics providing a static momentum acceptance of ±2% [11]. While the dynamic acceptance needs more development, the double-ring scheme helps mitigating the “orbit sawtooth” in the arcs [12]. The beamstrahlung also enlarges the equilibrium energy spread and the bunch length by a multi-turn buildup [13], as simulated [14] and also estimated analytically — an effect which has consistently been taken into account in Table 3.

One of the merits of a circular e^+e^- collider is that the expected energy spectrum is much narrower than for a linear collider. This advantage is natural since the beamstrahlung of a ring collider must be sufficiently small in order to remain within the available acceptance, as otherwise the required minimum beam lifetime is not achieved. An example result from a simulation (for LEP3) using the Guinea-Pig code [15] is shown in Fig. 2.

The beams of TLEP are expected to be partially polarized up to the W pair threshold. Indeed, scaling with the energy spread ($\propto E^2/\sqrt{\rho}$) suggests that TLEP at 81 GeV should achieve a polarization of a few percent, similar to LEP at 61 GeV [16]. At the Z resonance, polarization levels up to 60% or higher appear possible [17]. The polarization will allow for precise beam energy calibration using resonant depolarization applied to collision-free pilot bunches with long lifetime.

3. Conclusions

The technology and techniques for circular colliders are well established. SuperKEKB, to be commissioned from 2015, will demonstrate many, if not all, key concepts of the proposed TLEP e^+e^- Higgs factory. TLEP will allow extremely precise studies of Z, W, H and t [4]. By sharing the tunnel and much of the infrastructure, TLEP provides a cost-effective path towards a 100-TeV

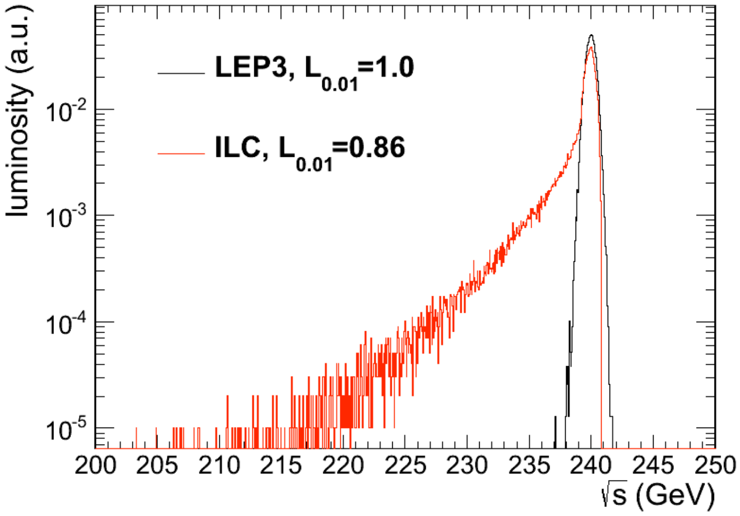

Figure 2: Comparison of energy spectrum at collision for the ILC (red) and LEP3 (black) [15]. Due to stronger beamstrahlung, energy spread and uncertainty are larger for the ILC than for LEP3 (or TLEP).

VHE-LHC *pp* collider — the "ultimate Higgs factory." The combination of TLEP, VHE-LHC and VHE-LHeC (*ep*) represents an exciting long-term vision for accelerator-based particle physics.

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