THE LHeC AS A HIGGS BOSON FACTORY

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Abstract

The LHeC is designed to collide a new 60 GeV energy electron beam, from a 3-pass ERL, with the 7 TeV energy LHC proton beam. At the present target ep luminosity of 10^{33} cm^{-2}s^{-1}, the LHeC would produce a few 1000 Higgs bosons per year, allowing for precision coupling measurements, especially of the $H \to b\bar{b}$ decay in charged current deep inelastic scattering ($ep \to \nu HX$). With a significant increase of the luminosity, rarer channels become accessible, as the charm decay. Here such an increase, to the level of 10^{34} cm^{-2}s^{-1} or even beyond, is considered from a combination of improvements, namely with a smaller proton beam emittance, with a further reduction of the proton IP beta function, an increase of the proton bunch intensity and with doubling the lepton beam current, compared to the canonical values assumed in the CDR.

LHeC BASELINE

The LHeC aims at colliding the high-energy protons and heavy ions circulating in the LHC with 60-GeV polarized electrons and possibly also positrons. The LHeC baseline configuration is realized by adding to the LHC a separate 9-km racetrack-shaped recirculating superconducting (SC) energy-recovery linac (ERL); see Fig. 1.

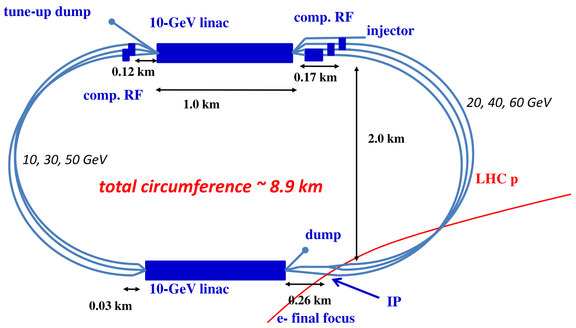

Figure 1: LHeC ERL layout including dimensions.

The key components of the LHeC are the two 1-km 10-GeV SC linacs of the ERL, comparable in scale to the 17.5-GeV SC linac of the European XFEL presently under construction in Germany. The LHeC ERL provides a design lepton beam current of 6.4 mA at the ep collision point, which is taken to be at interaction point (IP) 2 of the LHC. Aside from the IP2 interaction region (IR), the LHeC underground infrastructure is fully decoupled from the existing LHC tunnel. Two of the access shafts could be located on the CERN Prevessin and Meyrin sites.

The LHeC is designed to operate with simultaneous LHC p-p (or A-A) collisions in ATLAS, CMS, and LHCb. LHeC operation is fully transparent to the LHC experiments thanks to the low lepton bunch charge and resulting minuscule beam-beam tune shift experienced by the protons, together with the choice of the LHeC circumference to be equal to a third of the LHC's in order to allow for ion-clearing gaps in the ERL without perturbing LHC steady-state operation [1, 2].

LHeC has been designed under the constraint that the total electrical power for the LHeC lepton branch should not exceed 100 MW (about half the present maximum CERN site power). The LHeC electrical power budget is dominated by the RF and by the cryo power for the two 1-km long SC linacs. The cryo power and, therefore, also the size of the cryoplants (as well as the maximum lepton current) are directly linked to the unloaded quality factor of the cavities, Q_0. With a Q_0 of 2.5×10^{10} and a cavity gradient of 20 MV/m, the total main-linac cryopower is estimated at about 20 MW. The RF power needed for RF microphonics control is about 22 MW, and the extra-RF power needed for compensating SR losses at 6.4-mA current to 24 MW. The remaining components, like injectors or arc magnets, require a few MW each. Adding the contributions, together with rather conservative assumptions for most parameters, the LHeC ep target luminosity of 10^{33} cm^{-2}s^{-1} is achieved with 80–90 MW of wall-plug power [1].

LHeC HIGGS PHYSICS

After the discovery of a light Higgs boson, at a mass around 126 GeV by the ATLAS and CMS experiments in 2012, it was soon highlighted that the LHeC can support an attractive Higgs physics programme complementary to the LHC. Higgs studies at the LHeC would include: (1) precision coupling measurements such as $Hb\bar{b}$, $H\gamma\gamma$, $Hc\bar{c}$, $H4l$, etc., (2) the reduction of the QCD-related uncertainties in pp Higgs physics, and (3) the possibility to find new physics at the cleanly accessible WWH and ZZH vertices. These studies would benefit from a luminosity higher than the baseline. The cross section for Higgs production in ep collisions at the LHeC is about 200 fb for a 60-GeV electron beam with 80–90% polarization P_e [3]. The cross section for an unpolarized beam would be only 109 fb. The gain from polarization is related to the charged current cross section ($W^{\pm}$ exchange), which involves a factor $(1 - P_e)$. For a higher e^- energy of 140 GeV, the ep Higgs production cross section would be $\sim$400 fb.

LHeC *ep* HIGGS FACTORY

LHeC extensions to luminosity values significantly higher than the baseline, i.e. above 10^{34} cm^{-2}s^{-1}, can be realized through a combination of improvements, namely

(1) by increasing the proton bunch intensity from 1.7×10^{11} to the HL-LHC target values [4] of 2.2×10^{11} at 25-ns bunch spacing or 3.5×10^{11} at 50-ns spacing;

(2) by reducing the associated transverse normalized rms emittances from the present LHC design value of 3.75 μm

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Table 1: LHeC baseline and Higgs factory parameters.

parameter [unit]	LHeC baseline		LHeC Higgs factory	
species	e^-	p	e^-	p
beam energy (/nucleon) [GeV]	60	7000	60	7000
bunch spacing [ns]	25 (50)	25 (50)	25 (50)	25 (50)
bunch intensity (nucleon) [10^{10}]	0.1 (0.2)	17	0.4 (0.8)	22 (35)
beam current [mA]	6.4	860	25.6	1110 (883)
rms bunch length [mm]	0.6	75.5	0.6	75.5
polarization [%]	90	none	90	none
normalized rms emittance [μm]	50	3.75	50	2.5 (3.0)
geometric rms emittance [nm]	0.43	0.50	0.43	0.34
IP beta function $\beta^*_{x,y}$ [m]	0.12	0.1	0.039	0.05
IP spot size [μm]	7.2	7.2	4.1	4.1
synchrotron tune Q_s	—	1.9×10^{-3}	—	1.9×10^{-3}
hadron beam-beam parameter	0.0001 (0.0002)		0.0004 (0.0008)	
lepton disruption parameter D	6		23 (31)	
crossing angle	0		0	
hourglass reduction factor H_{hg}	0.91		0.70 (0.73)	
pinch enhancement factor H_D	1.35		1.35	
c.m. energy [GeV]	1300		1300	
luminosity / nucleon [10^{33} cm^{-2}s^{-1}]	1.3		16 (22)	

to the HL-LHC values of 2.5 μm at 25-ns bunch spacing or 3.0 μm at 50-ns spacing;

(3) by a further reduction of the LHeC proton IP beta function $\beta^*_{x,y}$ from 0.1 m down to 0.05 m, which should be possible by using a variant of the so-called ATS optics [5] (the latter can provide a $\beta^*_{x,y}$ down to 0.07 m in pp collisions with a much larger free length from the IP of 23 m, to be compared with 10 m at the LHeC [6], and with two squeezed proton beams to be accommodated in the final quadrupole aperture instead of one) — however, $\beta^* = 0.05$ m might render the final quadrupole and the magnet support structure in the cavern more challenging —-; and

(4) by increasing the lepton beam current: doubling the current should be possible without exceeding the 100-MW total wall-plug power limit if the unloaded Q_0 value of the SC RF cavities can be raised to 4×10^{10} (as it is assumed for the similar eRHIC design), also a quadrupling of the lepton current would be possible from the beam-dynamics and injector points of view, which however would result in a total wall-plug power of about 150 MW for the lepton branch of the LHeC.

Table 1 compares the baseline LHeC parameters with those of a higher-luminosity LHeC Higgs factory. The rise of the electron disruption D from 6 to about 30 does not increase the emittance after collision, so that the baseline arc aperture suffices. However, a kink instability may occur if [7] $D < D_{\rm thr} \equiv (16 Q_s/\beta^*_p)\sigma^{*2}\gamma_p/(N_e r_p)$, where N_e denotes the electron bunch population. The threshold $D_{\rm thr}$ amounts to 73 and 13 (8) for the baseline and Higgs factory, respectively. This indicates that the Higgs-factory parameters may be a factor 2–4 above the threshold. Stable beam operation can still be possible thanks to Landau damping or by virtue of nonzero chromaticity. For comparison, the eRHIC design disruption is a factor ~10 above the kink-instability threshold [7].

The precision for LHeC Higgs physics with positrons is inferior to that with electrons because the e^+ intensity is lower, e^+ polarisation difficult to achieve, and the H production cross section in e^+p smaller than with e^-p [3] due to low down/up quark distribution ratio.

Applying the same p parameter improvements as above, the luminosity of an alternative LHeC based on a pulsed straight linac [1] with an e^- energy of 140 GeV would exceed 10^{32} cm^{-2}s^{-1} (increased by a factor of 3).

SAPPHIRE $\gamma\gamma$ HIGGS FACTORY

A dedicated $\gamma\gamma$ Higgs factory, called "SAPPHiRE" [8], could be realized by slightly reconfiguring the LHeC recirculating linacs, which would, in this case, be operated without energy recovery as the electrons are consumed by Compton scattering off a high-power laser beam. The standard LHeC employs a pair of recirculating linacs capable of increasing the e^- energy by ~10 GeV in each pass. The $\gamma\gamma$ Higgs factory would require an electron beam energy of ~ 125 GeV/0.8/2 ~ 80 GeV, where the factor 2 arises from the centre-of-mass energy for two colliding beams, and the factor 0.8 approximates the peak of the $\gamma\gamma$ luminosity energy spectrum as fraction of the e^-e^- energy, considering typical Compton backscattering parameters. In SAPPHiRE the required electron energy could be achieved via four passes through two superconducting recirculating linacs, as is illustrated in Fig. 2. Compared to the LHeC, one additional arc is required on either side, corresponding to beam energies of 70 and 80 GeV, respectively. The 80-GeV arc is split into two halves with the $\gamma\gamma$ (e^-e^-) collision point at the centre. The two additional arcs can be placed in the 'existing' LHeC ERL arc tunnel, resulting in a total energy loss from synchrotron radiation over all 8 arcs of 3.9 GeV (about 5% of the final beam energy), which is

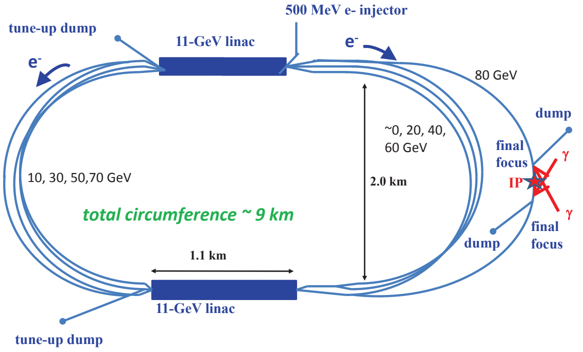

Figure 2: Sketch of a layout for a $\gamma\gamma$ collider, "SAPPHiRE," based on the LHeC recirculating SC linacs [8].

considered acceptable. Alternatively, for SAPPHiRE, the LHeC linacs could be operated in pulsed mode at a 33% higher cavity gradient of 26.7 MV/m, to reach an electron energy of 80 GeV in 3 passes, without the need of additional arcs. Table 2 compiles a list of example parameters, which would meet the SAPPHiRE luminosity target of $\mathcal{L}_{\gamma\gamma} \sim 6 \times 10^{32}$ cm^{-2}s^{-1} above 125 GeV (or equivalently $\mathcal{L}_{e^-e^-} \sim 2 \times 10^{34}$ cm^{-2}s^{-1}). The Compton IR with integrated optical cavity and the production of the required photon beam using a laser or FEL still require R&D effort.

Table 2: Example parameters for a $\gamma\gamma$ collider Higgs factory, "SAPPHiRE," based on the LHeC.

parameter	symbol	SAPPHiRE
total electric power	P	200 MW
beam energy	E	80 GeV
beam polarization	P_e	0.80
bunch population	N	10^{10}
repetition rate	$f_{\rm rep}$	cw
bunch frequency	$f_{\rm bunch}$	200 kHz
average beam current	$I_{\rm beam}$	0.32 mA
rms bunch length	σ_z	30 μm
crossing angle	θ_c	$\geq$ 20 mrad
horizontal emittance	$\gamma\epsilon_x$	5 μm
vertical emittance	$\gamma\epsilon_y$	0.5 μm
horiz. IP beta function	β_x^*	5 mm
vert. IP beta function	β_y^*	0.1 mm
rms hor. IP spot size	σ_x^*	400 nm
rms vert. IP spot size	σ_y^*	18 nm
rms hor. CP spot size	$\sigma_x^{C,*}$	400 nm
rms vert. CP spot size	$\sigma_y^{C,*}$	180 nm
e^-e^- geom. luminosity	$\mathcal{L}$	2×10^{34} cm^{-2}s^{-1}

CONCLUSIONS

The LHeC represents an interesting possibility for further efficient exploitation of the LHC infrastructure investment. At 60-GeV lepton beam energy and using the 7-TeV proton (and few TeV / nucleon ion) beam, centre-of-mass collision energies in the TeV range are attained. With two additional arcs in the same tunnel using 4 instead of 3 passes through the linacs — or, alternatively, with pulsed higher-gradient instead of cw operation keeping the 3 passes — the LHeC could also operate as Higgs factory $\gamma\gamma$ collider (SAPPHiRE).

In particular, the various LHeC configurations allow for unique Higgs physics studies. A high-luminosity set up, with minimum IP beam size and maximum lepton current, can deliver about 40k Higgs bosons per year (10^7 seconds) in ep collisions, while LHeC-SAPPHiRE could produce about 10k Higgs bosons per year in $\gamma\gamma$ collisions, both opening up new horizons in high-precision Higgs measurements. Table 3 compiles the performance of the LHeC and LHeC-SAPPHiRE based Higgs factories.

The anticipated development of a CW SC recirculating energy-recovery linac for LHeC would prepare for many possible future projects, e.g., for a circular high-luminosity e^+e^- Higgs factory (TLEP) [9], which could also be configured as a "TLHeC" $e^\pm p$ collider with luminosities between 10^{34} and 10^{35} cm^{-2}s^{-1}, for an International Linear Collider, for a neutrino factory, for a proton-driven plasma wake field accelerator, or for a muon collider.

Table 3: LHeC Higgs factory comparison (where 1 year is taken to be 10^7 s at design luminosity).

machine	LHeC	LHeC-HF	SAPPHiRE
luminosity [10^{34} cm^{-2}s^{-1}]	0.1 (ep)	2 (ep)	0.06 ($\gamma\gamma$ > 125 GeV)
cross section	~200 fb	~200 fb	>1.7 pb
no. Higgs/yr	2k	40k	>10k

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