THE LARGE HADRON-ELECTRON COLLIDER (LHeC) AT THE LHC

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Abstract

Sub-atomic physics at the energy frontier probes the structure of the fundamental quanta of the Universe. The Large Hadron Collider (LHC) at CERN opens for the first time the 'terascale' (TeV energy scale) to experimental scrutiny, exposing the physics of the Universe at the sub-attometric ($\sim 10^{-19}$ m, 10^{-10} as) scale. The LHC will also take the science of nuclear matter to hitherto unparalleled energy densities. The hadron beams, protons or ions, in the LHC underpin this horizon, and also offer new experimental possibilities at this energy scale. A Large Hadron electron Collider, LHeC, in which an electron (positron) beam of energy 60 to 140 GeV is in collision with one of the LHC hadron beams, makes possible terascale lepton-hadron physics. The LHeC is presently being evaluated in the form of two options, 'ring-ring' and 'linac-ring', either of which operate simultaneously with pp or ion-ion collisions in other LHC interaction regions. Each option takes advantage of recent advances in radio-frequency, in linear acceleration, and in other associated technologies, to achieve ep luminosity as large as 10^{33} cm^{-2}s^{-1}.

INTRODUCTION

The LHC is due to provide first high-energy proton-proton collisions later in 2009. A planned two-phase LHC upgrade aims at increasing the LHC pp luminosity to ten times the nominal, namely to 10^{35} cm^{-2}s^{-1}, by 2018.

The LHC physics programme would be complemented and greatly extended through ep collisions at highest energy and luminosity, which could be realized by colliding the 7-TeV protons of LHC with an electron or positron beam of 60–140 GeV. There is great interest from particle physics in studying both e^-p and e^+p collisions at this energy scale. Polarized beams might further enrich the physics potential. The possibility of such "LHeC" is being investigated under an ECFA mandate [1, 2, 3].

Two options are being considered: (1) a new lepton ring in the LHC tunnel [4, 5]; and (2) a superconducting electron linac, configured as recirculator [6]. We will refer to them as Ring-Ring (RR) and Ring-Linac (RL) options.

For the protons, the so-called ultimate LHC beam with $N_b = 1.7 \times 10^{11}$ protons per bunch at 25-ns spacing, together with a phase-I upgrade of the interaction region, should be available from 2014 onward. A phase-II (SLHC) upgrade option with 50 ns spacing and $N_b = 5 \times 10^{11}$, together with the possibility of further reduced proton interaction-point (IP) beta function could be realized by 2018. Key parameters for both these scenarios are compiled in Table 1. In the following, we will assume the parameters of the 50-ns option.

Table 1: LHC proton beam scenarios. "LHC" refers to the phase-I upgrade, "LHC*" to one of the proposed phase-II options.

	$N_{b,p}$	$T_{\rm sep}$	$\epsilon_p\gamma_p$	$\beta^*_{p,\rm min}$
LHC	1.7×10^{11}	25 ns	3.75 μm	0.25 m
LHC*	5×10^{11}	50 ns	3.75 μm	0.10 m

For the purpose of comparing different scenarios, we consider a constant electrical wall-plug power of 100 MW for the electron branch of the collider. To first order, the luminosity scales linearly with the power.

LUMINOSITY

The electron beam size is assumed to be matched to the size of the protons, $\sigma_p^* = \sigma_e^*$, as a smaller electron beam could have adverse effects on the proton beam lifetime. For round-beam collisions, the luminosity is

$$L = \frac{1}{4\pi e}\frac{N_{b,p}}{\epsilon_p}\frac{1}{\beta_p^*} I_e \, H_{\rm hg}, \quad (1)$$

where e denotes the electron charge, and the subindices p or e refer to protons or electrons. The luminosity (1) depends only on the p beam brightness $(N_{b,p}/\epsilon_p)$ with $N_{b,p}$ the number of protons per bunch and ϵ_p the geometric emittance, on β_p^*, on the electron beam current I_e, and on the hourglass factor $H_{\rm hg}$. The term $(N_{b,p}/\epsilon_p)$ is limited by space charge in the proton injector complex and by the pp beam-beam tune shift. The electron current I_e is limited by the available electrical power. The proton IP beta function β_p^* is confined, on the proton side, by the IR layout, as well as by the chromatic correction scheme, and on the electron side by the reduction factor due to the hourglass effect, $H_{\rm hg}$ which is a function of $(\beta_e^*/\sigma_{z,p})$ and (ϵ_e/ϵ_p) [6].

In case of an electron ring, a typical emittance at 60 GeV is $\gamma_e\epsilon_e \geq 2$ mm. Requiring $H_{\rm hg} > 0.9$ leads to $\beta_e^* > 2$ mm. Together with ϵ_p of Table 1, this translates into a lower limit for β_p^* of about 1 m. The electron beam-beam tune shift ΔQ_e adds an upper bound on β_e^*, and therefore a lower bound on ϵ_e, via $\beta_e^* \leq (4\pi/r_e)\gamma_e(\beta_p^*\epsilon_p/N_b)\Delta Q_e$, which can be estimated as $\beta_e^* \leq 50$–500 mm (depending on β_p^*).

For the e$^-$ linac, there is no lower bound on ϵ_e, as the disruption parameter replaces the tune shift as constraint, and, with the lower linac emittance, the hourglass reduction remains acceptable for β_p^* values as low as 0.1 m [6].

POWER AND ENERGY

In the RR case, the maximum beam energy and beam current are linked through the synchrotron-radiation (SR) power loss $P_{\rm SR} \approx 0.4$ MW I_e[mA] $(E_b/60$ GeV$)^4$, according to which the beam current and luminosity decrease as the inverse 4th power of beam energy. The SR losses are compensated by a superconducting (SC) radiofrequency (RF) system. With typical efficiencies of RF power sources, the wall plug power is about twice the SR power. Parasitic energy losses in the SC cavities might also prove important [7].

In the RL case, the RF power is used for acceleration. The maximum beam current is limited by the linac RF power, $P_{\rm RF} = (I_e/e)E_b 1/(1-\eta_{\rm ER})$, where we indicate the potentially large beneficial effect of optional energy recovery with an efficiency $\eta_{\rm ER}$. As for the ring, the wall-plug power to RF conversion efficiency is about 50% for SC linacs. In continuous-wave (CW) operation the RF to beam power conversion is close to 100%. The cryopower determines the choice of the acceleration gradient and duty factor. The cryogenics electric power can be written as $P_{\rm cryo} = AE_b/g + BDE_b g$, with $A \approx 350$ W/m and $B \approx 5 \times 10^{-11}$ Wm/(eV)^2, where g denotes the average accelerating gradient in units of eV/m, D the RF duty factor, E_b the energy gain over the length of the linac, and the coefficients A and B were inferred from the 1.3-GHz ILC and XFEL designs (scaling to 700 MHz) [5, 8].

CONFIGURATIONS

General RR and RL LHeC layouts are sketched in Fig. 1. The RR option is quite similar to LEP, except that, at 60–80 GeV beam energy, the RR-LHeC will operate with 1400–2800 bunches instead of 8–12, and with a significantly higher beam current above 100 mA, to be compared with about 6 mA at similar beam energies in LEP. The electron ring would be installed in the existing LHC tunnel and its RF be located in new tunnels of several hundred meter lengths which are foreseen to bypass then operating LHC experiments [9]. A crossing angle of 1–2 mrad may be required to control the effect of long-range beam-beam collisions and the SR fan in the interaction region [4]. In order to compensate for the finite crossing angle it is desirable in the RR option to foresee the installation of crab cavities, which is similarly under consideration for the LHC phase-II upgrade. The high-energy part of the planned 4 or 5-GeV SC Proton Linac (SPL) could also serve as e^- injector for the ring, possibly complemented with a recirculation loop.

The linac for the RL option is similar to the XFEL and ILC, but it also requires a higher beam current than these two linacs. Operation as a recirculating linac is conceivable. A construction-cost optimization suggests that for a final beam energy between 60 and 140 GeV, a single recirculation loop is the cost minimum [10]. The bending radius in this loop can be chosen large enough, e.g. 1.5 km, that the SR energy loss does not exceed 2% at a recirculation energy of 70 GeV (corresponding to 140 GeV final energy). This choice opens the possibility of another, higher luminosity running mode: at energies lower than 75 GeV the spent beam after collision can be recirculated via the same arc, thereby allowing for recovery of most of its energy, and boosting the luminosity at constant wall plug power. Concerns for the linac are the construction cost and the fairly high beam current, as well as the e^+ source.

Possible linac parameters for three different beam energies are summarized in Table 2. Figure 2 shows preliminary linac beta functions as well as the beam energy as a function of distance for the 60-GeV RL configuration with four passes and energy recovery. In this example the optics becomes unstable during deceleration at an energy around 15 GeV, implying an energy recovery efficiency $\eta_{\rm ER}$ near 75%. Further optics development is underway.

Table 3 compares beam parameters of various LHeC RR and RL versions with those of the XFEL and ILC projects.

Table 2: Recirculating linac parameters for LHeC-RL.

LHeC-RL scenario	lumi	baseline	energy
final energy [GeV]	60	100	140
cell length [m]	24	24	24
cavity fill factor	0.7	0.7	0.7
tot. linac length [m]	3000	2712	3024
cav. gradient [MV/m]	13	25	32
operation mode	CW (ERL)	pulsed	pulsed

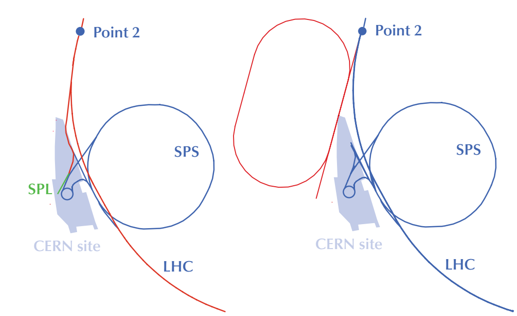

Figure 1: RR (left) & RL (right) LHeC layouts [11].

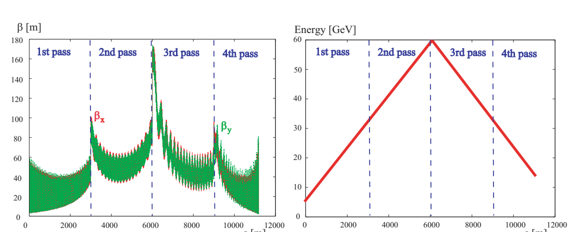

Figure 2: Beta functions (left) and beam energy (right) during two accelerating and two decelerating passes through the same linac for the LHeC-RL high-luminosity ERL option [the return arcs are not shown].

Table 3: Example LHeC-RR and RL parameters. Numbers for LHeC-RL high-luminosity option marked by '†' assume energy recovery with $\eta_{\rm ER} = 90\%$; those with '‡' refer to $\eta_{\rm ER} = 0$. ILC and XFEL numbers are included for comparison. Note that optimisation of the RR luminosity for different LHC beam assumptions leads to similar luminosity values of about 10^{33} cm^{-2}s^{-1} [12].

	LHeC-RR	LHeC-RL high lumi	LHeC-RL 100 GeV	LHeC-RL high energy	ILC	XFEL
e$^-$ energy at IP [GeV]	60	60	100	140	(2×)250	20
luminosity [10^{32} cm^{-2}s^{-1}]	29	29† (2.9‡)	2.2	1.5	200	N/A
bunch population [10^{10}]	5.6	0.19† (0.02‡)	0.3 (1.5)	0.2 (1.0)	2	0.6
e$^-$ bunch length [μm]	∼10,000	300	300	300	300	24
bunch interval [ns]	50	50	50 (250)	50 (250)	369	200
norm. hor.&vert. emittance [μm]	4000, 2500	50	50	50	10, 0.04	1.4
average current [mA]	135	7† (0.7‡)	0.5	0.5	0.04	0.03
rms IP beam size [μm]	44, 27	7	7	7	0.64, 0.006	N/A
repetition rate [Hz]	CW	CW	10 [5% d.f.]	10 [5% d.f.]	5	10
bunches/pulse	N/A	N/A	71430	14286	2625	3250
pulse current [mA]	N/A	N/A	10	10	9	25
beam pulse length [ms]	N/A	N/A	5	5	1	0.65
cryo power [MW]	0.5	20	4	6	34	3.6
total wall plug power [MW]	100	100	100	100	230	19

INTERACTION REGION (IR)

Several points are to be considered for the IR design: (1) the focusing to small $\beta^*_{p,e}$, which favors quadrupole magnets close to the IP; (2) the separation of the two beams either with a crossing angle, requiring proton crab cavities, or with a bending system [6], raising issues of SR shielding, and parasitic collisions; (3) the particle-physics request for a large angular acceptance of at least 10°, but preferably 1°. In view of the smaller e$^-$ beam divergence at the collision point, the detector acceptance for the RL option is likely to be larger than for RR. An interesting proposal for LHeC is a superconducting magnet calorimeter, which would be part of the detector and of the machine [13].

LEPTON SOURCES

The e$^-$ beam for the linac can be produced from a polarized dc gun with a normalized rms emittance between 10 and 100 μm.

While for LHeC-RR a rebuilt conventional e$^+$ source would suffice, the e$^+$ production for LHeC-RL is a true challenge. LHeC requires at least 10 times more e$^+$'s per unit time than the ILC (Table 3). In addition, the large number of bunches per pulse or the CW operation would make it difficult to shrink the e$^+$ emittance in a damping ring. Candidate polarized e$^+$ production schemes for LHeC-RL include an ERL Compton source for CW operation, and either an undulator source using the spent e$^-$ beam or a linac-Compton source for pulsed operation. As an example, the e$^-$ beam from a 100 mA ERL could Compton scatter off 0.6 J laser pulses in 10 optical cavities, generating 4.8×10^{10} γ's/bunch, which upon hitting a target would create 4×10^8 e$^+$/bunch. Any margin could be used to reduce the emittance by collimation. Another proposal is extremely fast damping in a laser cooling ring. A further idea for 60-GeV ERL operation is to not only recover the energy, but also to recycle a large fraction of the e^+ with good emittance, relaxing the e$^+$ source requirements.

CONCLUSIONS

An LHeC could provide high-energy high-luminosity e$^\pm$p and e$^\pm$A collisions. Two major designs are under study, a ring-ring option with luminosities of 10^{33} cm^{-2}s^{-1} and energies limited to 80 GeV, and a linac-ring option with similar luminosity using energy recovery and the possibility of an extension to higher energies. Injection to the ring may be provided by operating the SPL as an electron accelerator, possibly complemented by recirculation to reach a few tens of GeV electron beam energy.

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