DESIGN CONCEPTS FOR THE LARGE HADRON ELECTRON COLLIDER

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Abstract

A report is presented on the design concepts for a high luminosity electron-nucleon collider of 1.3 TeV centre of mass energy, realized with the addition of a 60 GeV electron ring or linear accelerator to the existing proton and ion LHC beam facility.

INTRODUCTION

Based on an extensive report [1], which at the time of IPAC11 exists as a first draft [1], main design considerations and solutions are presented of a new electron-hadron collider, the LHeC, in which electrons of 60 to possibly 140 GeV collide with LHC protons of 7000 GeV. With an ep design luminosity of about $10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, the Large Hadron Electron Collider exceeds the integrated luminosity collected at HERA by two orders of magnitude and the kinematic range by a factor of twenty in the four-momentum squared, Q^2, and in the inverse Bjorken x. The physics programme is devoted to an exploration of the energy frontier, complementing the LHC and its discovery potential for physics beyond the Standard Model with high precision deep inelastic scattering (DIS) measurements. These are projected to solve a variety of fundamental questions in strong and electroweak interactions. The LHeC thus becomes the world's cleanest high resolution microscope, designed to continue the path of deep inelastic lepton-hadron scattering into unknown areas of physics and kinematics. The physics programme also includes electron-ion (eA) scattering into a $(Q^2,\ 1/x)$ range extended by four orders of magnitude as compared to previous lepton-nucleus DIS experiments, which will revolutionise the physics of the partonic nuclear medium.

The LHeC may be realised either as a ring-ring (RR) or as a linac-ring (LR) collider. A choice between the two options will precede the technical design phase which begins in 2012. The design is for synchronous pp and ep operation to be able to collect high integrated luminosity with the LHeC as is required for rare and new physics processes, preferentially occuring at high Q^2 and large Bjorken x. Following current and tentative time schedules, which account time for the TDR, the civil engineering, the industrial production of the about 5000 magnet and cavity components and their installation, the LHeC may begin its operation in 2023, when the LHC commences its second, the maximum luminosity phase of operation.

LAYOUTS

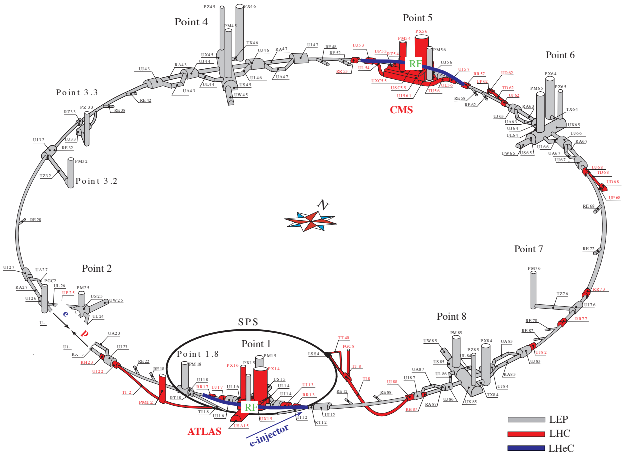

Figure 1: Schematic Layout of the LHC (grey/red) with the bypasses of CMS and ATLAS for the ring electron beam (blue) in the RR version. The e injector is a 10 GeV superconducting linac in triple racetrack configuration which is considered to reach the ring via the bypass around ATLAS.

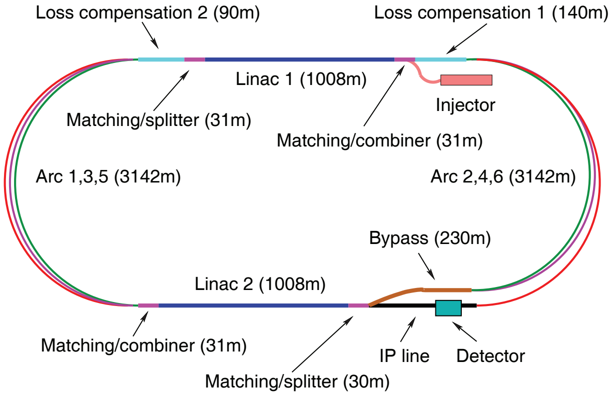

Figure 2: Schematic layout of the 60 GeV linac in racetrack configuration. The circumference matches $1/3$ of the LHC.

The default electron beam energy is chosen to be 60 GeV. For the design study it has been assumed that ep collisions take place at point 2 which currently houses the ALICE experiment. The electron ring (Fig. 1) bypasses CMS and ATLAS towards the outside of the ring in separate tunnels of about 1.3 km length each, which also host the electron rf and cryogenics equipment. A similar bypass may be foreseen for the LHCb experiment. The maximum energy one may achieve with the ring arrangement could reach about 120 GeV requiring, however, many parameters

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[1] The list of authors can be found in [1].

to be extreme as the rf power and synchrotron radiation effects increase $\propto E_e^4$. The linac layout (Fig. 2) is similarly optimised for luminosity and cost. This results in two s.c. linacs of 1 km length each, which are traversed three times to achieve the 60 GeV energy while the luminosity is enhanced, by likely more than an order of magnitude, using energy recovery by decelerating the spent beam. Energies significantly higher than 60 GeV can be achieved with a straight linac arrangement for which a principle design, choosing 140 GeV, is included in the design report, possibly complemented with 10 GeV stages for energy recovery.

PARAMETERS

The parameters of the ep collider are determined by the LHC hadron beams. A selection of the parameters is given in Tab. 1 for $E_e = 60$ GeV. For the RR configuration, the $\beta_{x,y}$ functions and luminosity values correspond to the 1° optics, in which the first e beam magnet is placed 6.2 m apart from the IP. In a further, the high luminosity option the β functions are smaller and the luminosity is enhanced by a factor of 2. This is achieved by placing the first magnet at 1.2 m distance from the IP which restricts the polar angle acceptance to $8 - 172°$. The e^+ intensity value in the LR configuration reflects current expectations and may be surpassed with dedicated R&D. The LR luminosity may be reduced to about 2/3 for a clearing gap to avoid fast ion instabilities, at fixed bunch intensity.

Table 1: Parameters of the RR and RL Configurations

	Ring	**Linac**
electron beam		
beam energy E_e	60 GeV	
e^- (e^+) per bunch N_e [10^9]	20 (20)	1 (0.1)
e^- (e^+) polarisation [%]	40 (40)	90 (0)
bunch length [mm]	10	0.6
tr. emittance at IP $\gamma\epsilon^e_{x,y}$ [mm]	0.58, 0.29	0.05
IP β function $\beta^*_{x,y}$ [m]	0.4, 0.2	0.12
beam current [mA]	131	6.6
energy recovery intensity gain	–	17
total wall plug power	100 MW	
syn rad power [kW]	51	49
critical energy [keV]	163	718
proton beam		
beam energy E_p	7 TeV	
protons per bunch N_p	$1.7 \cdot 10^{11}$	
transverse emittance $\gamma\epsilon^p_{x,y}$	3.75 μm	
collider		
Lum e^-p (e^+p) [10^{32}cm^{-2}s^{-1}]	9 (9)	10 (1)
bunch spacing	25 ns	
rms beam spot size $\sigma_{x,y}$ [μm]	30, 16	7
crossing angle θ [mrad]	1	0
$L_{eN} = A\, L_{eA}$ [10^{32}cm^{-2}s^{-1}]	0.3	1

COMPONENTS

Parameters of magnet, rf and cryogenics components for the RR and the LR configuration are summarised in Tab. 2. The total number of magnets (dipoles and quadrupoles excluding the few special IR magnets) and cavities is 4058 for the ring and 6132 for the linac. The majority are the 3080 (3600) normal conducting dipole magnets of 4 (5.4) m length for the ring (linac return arcs) for which first prototypes have been successfully built at BINP Novosibirsk and at CERN. The number of high quality cavities for the linac is below 1000. Based on SPL developments, currently a frequency of 721 MHz is chosen. The cavity is operated in CW mode at about 20 MV/m for the energy recovery configuration at 60 GeV. The cavity demands of the LHeC are therefore considerably lighter than those from the ILC.

The cryogenics system of the ring accelerator is of modest demand. For the linac it critically depends on the cooling power per cavity which for the draft design is assumed to be 32 W at 2° K. This leads to a cryogenics system with a total electric grid power of 21 MW. The projected development of a cavity-cryo module for the LHeC, in conjunction with ongoing developments for the SPL at CERN and eRHIC at BNL, is directed to achieve a high Q_0 value and to reduce the dissipated heat per cavity.

Table 2: Components of the Electron Accelerators

	Ring	**Linac**
magnets		
beam energy	60 GeV	
number of dipoles	3080	3600
dipole field [T]	$0.013 - 0.076$	$0.046 - 0.264$
total nr of quads	866	1588
RF and cryogenics		
number of cavities	112	944
gradient [MV/m]	11.9	20
RF power [MW]	49	39
cavity voltage [MV]	5	21.2
cavity R/Q [Ω]	114	285
cavity Q_0	–	2.5 10^{10}
cooling power [kW]	5.4@4.2 K	30@2 K

Special attention is devoted to the interaction region design, which comprises beam bending, direct and secondary synchrotron radiation, vacuum and beam pipe demands. It requires a number of focussing magnets with apertures for the two proton beams and field-free regions to pass the electron beam after the IP. The field requirements for the ring-ring option (gradient of 127 T/m, beam stay clear of 13 mm (12 σ), aperture radius of 21 (30) mm for the p (e) beam) allow a number of different magnet designs using the well proven $NbTi$ superconductor technology and making use of the cable (MQY) development for the LHC. The requirements for the linac are more demanding in terms of an about twice larger gradient and tighter aperture constraints which may be met better with Nb_3Sn superconductor technology. The preferred design for the two nearest quadrupoles is shown in Fig. 3.

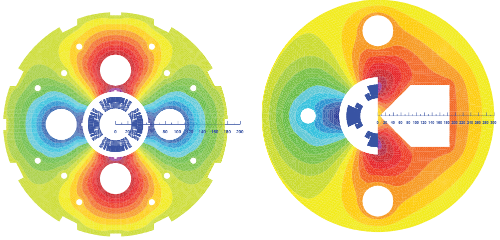

Figure 3: Cross-sections of the insertion quadrupole magnets for the linac-ring option. Left: Single aperture quadrupole (Q_2). Right: Half quadrupole with field-free region (Q_1).

First considerations have been made for the civil engineering. The ring requires for each bypass a new tunnel of about 1.3 km length. The ring injector has a length of about 150 m and may be placed at the Prevessin site on surface, which would require a transfer tunnel to reach the ATLAS bypass, or possibly in a new cavern underground. The 60 GeV racetrack arrangement for the linac requires a new tunnel of about 9 km length. It is envisaged to place it inside the LHC, at the depth of the LHC, in order to minimize the interference with land surrounding the CERN site. With modern tunnel boring machines one can expect to advance about 150 m per week which corresponds to 60 weeks for drilling the whole LHeC linac tunnel. Drilling a bypass can be made within about 10 weeks, which is comparable to an annual LHC shutdown time.

DETECTOR

The physics program depends on a high level of precision, as for the measurement of α_s, and on the reconstruction of complex final states, like the charged current single top production and decay or the precision measurement of the b-quark density. The detector acceptance has to extend as close as possible to the beam axis because of the interest in the physics at low and at large Bjorken x. The dimensions of the detector, sketched in Fig. 4, are constrained by the radial extension of the beam pipe in combination with maximum polar angle coverage, desirably down to about 1° and 179° for forward going final state particles and backward scattered electrons at low Q^2, respectively. A further general demand is a high modularity enabling much of the detector construction to be performed above ground for keeping the installation time at a minimum, and to be able to access inner detector parts within reasonable shut down times. The time schedule of the project demands to have a detector ready within about ten years. This prevents any significant R&D program to be performed. The choice of components fortunately can rely on the vast experience obtained at HERA, the LHC, including its detector upgrades to come, and on detector development studies for the ILC.

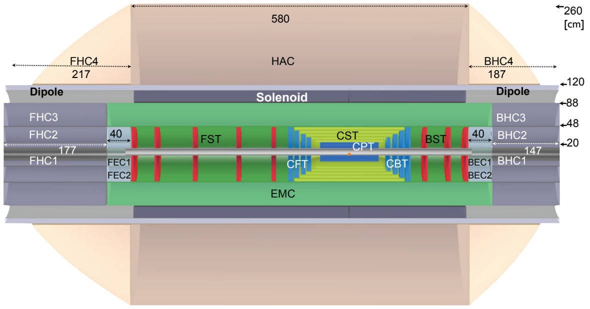

Figure 4: An rz cross section of the LHeC detector. In the central barrel, the following components are considered: a central silicon pixel detector (CPT); silicon tracking detectors (CST,CFT/CBT) of different technology; an electromagnetic LAr calorimeter (EMC) surrounded by a 3.5 T solenoid and a dipole magnet (for LR only) followed by a hadronic tile calorimeter (HAC) serving also as flux return. Not shown is the muon detector. The electron at low Q^2 is scattered into the backward silicon tracker (BST) and its energy is measured in the BEC and BHC calorimeters. In the forward region components are placed for tracking (FST) and calorimetry (FEC, FHC) of TeV energy final states.

STATUS AND NEXT STEPS

The draft design report is the result of a three years process, under the auspices of CERN, ECFA and NuPECC. Currently the report is being reviewed by referees appointed by the CERN directorate, for the physics, accelerator, detector and special aspects of the project, including a cost estimate. The updated report is being prepared for publication. The LHeC has to run while the LHC is still operational. This defines 2023 (the long shutdown LS3) as the natural and mandatory timeline of its realization. The tentative schedule foresees to begin the rf and magnet production in 2016, and the civil engineering in 2017. This requires preseries and legal preparations in the about two years before. A TDR has to be worked out until 2014. First critical components under consideration for design in 2012 are: an rf and cryomodule, a 1:1 dipole prototype and a prototype of the s.c. combined function magnet near the IP.

The LHeC represents a unique opportunity for building and operating a further TeV energy scale collider. It builds on the gigantic investments in the LHC and its intense hadron beams. The Tevatron, LEP and HERA have established the Standard Model (SM) of particle physics. The LHC, a pure lepton collider and the LHeC are expected to explore it at deeper levels and to eventually lead the exploration of the smallest dimensions beyond the current SM.

REFERENCES

[1] LHeC Study Group, “A Large Hadron Electron Collider at CERN”, Draft Design Report, LHeC-Note-2011-003 GEN, to be published (2011).