A Large Hadron Electron Collider at CERN - the LHeC

Conceptual Design Report

LHeC Collaboration

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Draft 0.1

Abstract

The physics programme and the design are described of a new $e^{\pm}p/A$ collider based on the LHC. The Large Hadron Electron Collider extends the kinematic range of HERA by two orders of magnitude in four-momentum square Q^2 and Bjorken x, and its design achieves a factor of hundred higher luminosity, of $\mathrm{O}(10^{33})\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The LHeC thus becomes the world's cleanest high resolution microscope and a crucial instrument to resolve the expected new physics at the TeV scale of mass and to also continue the path of deep inelastic lepton-hadron scattering into unknown areas of physics and kinematics. The LHeC may be realised as a ring-ring or linac-ring collider, and thorough design considerations are presented for both options in terms of their physics reach and technical realisation. Corresponding designs of interaction regions are presented as is a complete study of a suitable detector including tagging devices in forward and backward directions. The LHeC may be built, installed and operated while the LHC is still in operation. It thus represents a major opportunity for particle physics to progress and for the LHC to be further exploited.

1 Introduction

1.1 Deep Inelastic Scattering and Particle Physics

Somehow it began with [1] ...
- From MIT-SLAC to HERA
- Status of the Exploration of Nuclear Structure
- Open Issues in Quantum Chromodynamics
- Physics at the Tera Scale - First LHC Results

1.2 Physics Potential

- Partonic structure and substructure
- exploring superhigh energy scales and unification
- investigate the TeV energy scale physics, complementary to LHC
- discover saturation
- parton dynamics in the proton and in nuclei

1.3 Machine and Detector

- Requirements in terms of energy, lumi, beams and operation
- Basic Configurations
- Detector Considerations

1.4 Organisation and Considerations of the CDR

- Description of assumptions and aims
- Organisation of write up

2 Executive Summary

3 Design Considerations for the LHeC

3.1 Kinematics and Acceptance

3.2 Basic Configurations

3.3 Compatibility with the LHC

3.4 Deuterons and Heavy Nuclei

3.5 Scenarios for Physics and Detector Simulation

4 Precision QCD and Electroweak Physics

4.1 Inclusive Measurements

4.1.1 Cross Sections

4.1.2 Structure Functions F_2, F_L, xF_3, $F_2^{\gamma Z}$

4.2 Precision Measurements

4.2.1 QCD Fit Assumptions and Basic Results

4.2.2 Projected Accuracy of α_s

4.2.3 Weak Coupling Constants

4.3 Physics at Large Bjorken x

4.3.1 Theoretical Interest

4.3.2 Relation to LHC

4.3.3 Gluon Distribution

4.3.4 Light Quarks (d/u)

4.4 Strange, Charm and Beauty Densities

4.4.1 Experimental Conditions

4.4.2 Measurement of s and $\bar{s}$ in Charged Currents

4.4.3 $F_2^{c\bar{c}}$ and Intrinsic Charm

4.4.4 $F_2^{b\bar{b}}$

4.5 Single t and $\bar{t}$ Production

4.6 High p_T Jets

4.6.1 Experimental Conditions and Scale Uncertainties

4.6.2 Differential Cross Sections

4.6.3 Gluon Density and α_s

4.6.4 Final State Physics

4.7 Partonic Structure of the Photon

5 New Physics at Large Scales

5.1 Physics beyond the Standard Model in ep

5.2 New Particles or Interactions

5.2.1 Electron-Quark Resonances

5.2.2 New Leptons

5.2.3 Mass Measurements in RP conserving SUSY

5.3 Higgs Physics at the LHeC

5.4 Resolving Ambiguities

5.4.1 Discrimination of Z' Models

5.4.2 Ambiguities between eeqq Contact Interactions

5.4.3 New Physics at the LHC and pdf Effects - DY, dijets

5.5 New Particles or Interactions in γp Collisions

6 ep Physics at High Parton Densities

6.1 Introduction - Physics at small x

6.1.1 Unitarity and QCD

6.1.2 Models motivated by HERA data

6.1.3 Low-x physics at the LHC

6.1.4 Implications for ultrahigh energy neutrino interactions

6.2 Present Status

6.3 Inclusive measurements and structure functions

a. Predictions from different approaches for proton and nuclei (J. Albacete, A. Stasto, N. Armesto) *(plots of the comparison of different predictions and the pseudodata) [2]*

b. F_2, F_L pseudodata for proton and Pb vs. (x, Q^2) for varying electron beam energies (P. Newman, M. Klein, N. Armesto) *[2]*

c. Impact of $F_2/F_L/F_2^c$ ep and eD pseudo-data on DGLAP fits to the low-x nucleon structure (to be agreed with the QCD/EW group) (J. Rojo, M.Klein) *[2]*

d. Impact of pseudo-data on DGLAP fits to nuclei (C. Salgado, K. Eskola, H.Paukkunen) *[1]*

e. Testing the observability of non-linear dynamics from $F_2/F_L/F_2^c$ ep and eA data (J. Rojo, M. Klein, N. Armesto, P. Newman) *[1]*

6.4 Inclusive diffraction

6.5 Exclusive Vector Meson Production

6.6 DVCS and Generalised Parton Distributions

6.7 Jets and Multi-Jet Parton Dynamics

6.8 Unintegrated Parton Distributions

7 DIS Scattering off Nuclei [IF eA SEPARATE]

7.1 Experimental Conditions

7.2 Neutron Measurements

7.2.1 Fermi Motion and Proton Tagging

7.2.2 Shadowing and Diffraction

7.2.3 Partons in the Neutron

7.3 Heavy Ions

7.3.1 Simulations

7.3.2 Parton Distributions in Nuclei

7.3.3 Saturation

7.3.4 Appearance of the Black Disk Limit

7.3.5 Relation to the Physics of the QGP

8 LHeC as a Ring-Ring Collider

8.1 Baseline Parameters and Configuration

8.1.1 General Considerations

8.1.2 Design Parameters

8.1.3 Layout Overview

8.2 Lattice design

8.2.1 Lattice of the main arcs

8.2.2 Bypass

8.2.3 IR layout and optics

8.3 Lepton Beam Polarisation

8.4 RF design

8.4.1 Design Parameters

8.4.2 Cavities and klystrons

8.4.3 Proton crab cavity

8.5 Injector complex design

8.5.1 Electron and positron source

8.5.2 Injector

8.5.3 Heavy Ions

8.6 Injection areas and beam dump aspects

8.6.1 Transfer line

8.6.2 Beam dump line

8.7 Beam-Beam effects

8.7.1 Head-on beam-beam limit

8.7.2 Long range beam-beam effects and required crossing angle

8.7.3 Multi bunch beam-beam effects

8.7.4 Coupling between p-p and p-e collisions

8.8 Impedance

8.8.1 Resistive wall instability threshold and surface resistivity

8.8.2 TMCI instability threshold estimation

8.8.3 Multi-bunch instability estimates

8.8.4 Electron cloud estimates (positron-proton collisions)

8.8.5 Fast ion instability estimates

8.8.6 Specification of required feedback systems

8.9 Vacuum aspects

8.9.1 Specification of vacuum requirements

8.9.2 Layout vacuum design

8.9.3 Vacuum Engineering

bellows, plug in modules, magnet chambers...

8.9.4 Vacuum studies

8.9.5 Vacuum Instrumentation and Interlocks

8.10 Integration and machine protection issues

8.10.1 Space requirements

8.10.2 Bypassing the pp experiments

8.10.3 Impact of the synchrotron radiation on the electronics in the tunnel

8.10.4 Compatibility with the proton beam loss system

8.10.5 Space requirements for the electron dump

8.10.6 Protection of the p-machine against heavy electron losses

8.10.7 How to combine the Machine Protection of both rings?

8.11 Magnets

8.11.1 Main dipole - design and prototype

8.11.2 Quadrupole and corrector magnets

8.11.3 Magnet infrastructure specification

(cooling, ventilation etc...)

8.11.4 Specification of space and support requirements

8.12 Powering

Specification of space and infrastructure requirements

8.13 Installation of the ring accelerator

9 LHeC as a Linac-Ring Collider

9.1 Baseline Configurations

9.1.1 General Considerations

rf gradient, CLIC based?, cooling power, rf power, dc vs pulsed operation

9.1.2 Envisaged Parameters

luminosity, polarisation, energy and length limitations, tunnel

9.1.3 Two Baseline Layouts

- 60 GeV pulsed LINAC in 3km tunnel with dogbones
- 60 GeV ERL or 140 GeV pulsed in 12 km racetrack tunnel

9.1.4 High Intensity Positrons

9.1.5 Energy Recovery

9.1.6 Optimization of IR and beam parameters

9.1.7 Proton Beam Parameters

9.1.8 Photon-Proton Collider Option

9.2 RF design

total length, required cavities, power etc.

9.3 Spent-beam line and beam dump

9.4 Linac source

9.4.1 Polarized electron source design

- DC gun with preparation chamber for photo-cathode
- Laser system
- Pre-injector Linac for e- (5 MeV)

9.4.2 Unpolarized positron source design

- Thermionic gun
- Primary Linac (2 - 5 GeV range)

- Target with AMD
- Pre-injector Linac for e+ (200 MeV)

9.4.3 Polarized positron source design

- RF gun
- Laser system
- Linac (1.3 - 1.8 GeV range)
- Compton ring
- Stacking cavity
- Target with AMD
- Pre-injector Linac for e+ (200 MeV)

9.5 Linac Lattice and Impedance

9.5.1 Layout and lattice design for the linac

9.5.2 Wake field and alignment tolerances

9.5.3 Beam breakup and emittance preservation

9.6 Beam-Beam effects

9.6.1 Head-on beam-beam limit

9.6.2 Long range beam-beam effects and required crossing angle

9.6.3 Coupling between p-p and p-e collisions

9.7 Vacuum aspects

9.7.1 Specification of vacuum requirements

9.7.2 Layout vacuum design

9.7.3 Vacuum Engineering

9.7.4 Vacuum studies

9.7.5 Vacuum Instrumentation and Interlocks

9.8 Integration and machine protection issues

9.8.1 Space requirements

in the electron injection and ejection areas
for the power converters and other electronics

for the electron dump
for the electronics in the LINAC

9.8.2 Impact of the synchrotron radiation on the electronics

9.8.3 Machine Protection System for the LINAC

9.8.4 Compatibility with the proton beam loss system

9.8.5 Protection of the p-machine against heavy electron losses

9.9 IR Layout for linac-ring scenarios

9.9.1 Head on vs Crossing Angle Options

9.9.2 Magnet and detector layout

9.10 IR optics

crab waist

9.11 Magnet issues

9.11.1 Magnet coil design

main dipole and quadrupole and corrector magnets

9.11.2 Magnet infrastructure specification

cooling, ventilation etc...

9.11.3 Specification of space and support requirements

9.12 Powering issues

9.13 Building the Linac

10 Interaction Region Design

10.1 Overview

10.1.1 The high luminosity IR

10.1.2 The large acceptance IR for RR

10.1.3 Head on Collision IR for LR

10.2 Optics

10.2.1 Proton Optics in the IR

10.2.2 Electron Optics

10.3 Geometry

10.3.1 Beam Separation

10.3.2 Bypass geometries - here?

10.4 Synchrotron Light

10.4.1 Power spectrum

10.4.2 Absorber Design

10.5 IR Magnet Design

10.5.1 Electron Triplet

10.5.2 Proton low β triplet

10.5.3 Crab Cavity

10.6 Detector Geometry

10.6.1 Integration of accelerator components into the detector

10.6.2 Beam pipe layout

11 Forward and Backward Detectors

11.1 Forward Detectors

11.1.1 Proton Tagger

11.1.2 Neutron Tagger

11.1.3 Deuteron Tagger

11.2 Backward Detectors

11.2.1 Electron Tagging

11.2.2 Photon Tagging

11.3 Measurement of the Luminosity

12 A Detector Design

12.1 Requirements on the Detector

12.1.1 Acceptance

12.1.2 Resolution and Calibration

12.1.3 Particle ID and Tagging

12.1.4 Technical Constraints

12.2 Magnet

12.2.1 Field homogeneity

12.2.2 Magnet concept

12.3 Tracker

12.3.1 Technical Requirements

12.3.2 Tracking Performance

12.3.3 Front-end Electronics and Readout

12.3.4 Infrastructure Detector Construction and Prototyping

12.3.5 Inner Tracker

12.3.6 Particle Identification / π^0 Suppression

12.4 Electromagnetic Calorimeter

12.4.1 Design Considerations

12.4.2 Spagetti Calorimeter (H1 type)

12.4.3 Photodetector

12.4.4 Calibration and Monitoring

12.4.5 Read-Out Electronics

12.4.6 Crystal Option of ECal

12.4.7 CALICE Type ECal

12.4.8 Layout of the ECal Parts

12.5 Hadronic Calorimetry

12.5.1 Design Considerations

12.5.2 Cu/Brass/Tungsten Calorimeter Spagetti Type

12.5.3 Photodetector

12.5.4 Calibration and Monitoring

12.5.5 R/O Electronics

12.5.6 Crystal option

12.7 Removable fwd/bwd Si-Tracker - (or Gossip)

12.8 Muon Detection -Tail Catcher -Magnet Config. Dependent

12.8.1 Design Considerations

12.8.2 Removable fwd/bwd Parts

12.9 Beam-Beam Counter - Level-0 Trigger

12.9.1 Requirements and Detector Configuration

12.9.2 Triggering Capabilities

12.10 Fast Forward Detector

12.10.1 Aim and Detector Position

12.10.2 Forward detector Performance

12.11 Very Forward Detector in Trigger

12.12 Zero Degree Calorimeter

12.12.1 Requirements of ZDC Construction

12.12.2 Simulation of ZDC

12.12.3 Technical Design

12.13 Forward Magnetic Spectrometers - Muon

12.14 Trigger, DAQ and Computing

12.14.1 Data Acquisition System and Trigger

12.15 Computing

12.15.1 Data Processing Model

12.15.2 Computer Resources for the Experiment

12.16 Integration and Services

12.16.1 Hall Facilities and Services

12.16.2 Facility Integration

12.16.3 Mechanical Integration

12.16.4 Subsystems Dimension Control

12.16.5 Cables, Utilities - Routing

12.17 Detector Assembly

12.17.1 Detector Interface (Machine Interface)

12.17.2 Environmental Safety and Health

12.17.3 Safety Analysis Issues

12.18 Electronics integration

12.19 Software Integration

12.20 Detector Control System

12.20.1 Technical Requirements

12.20.2 L1 DCS Architecture

12.21 Simulation and Detector Performance

12.21.1 Detector Simulation Software Packages

12.21.2 Event Reconstruction

12.21.3 MC Simulation

12.22 Detector Summary

13 Summary

Acknowledgement

Many thanks to all

References

[1] R. Feynman, Photon-Hadron Interactions, 1972, W.A. Benjamin, Inc. Massachussetts.

Appendix 1

Tasks for a Technical Design Report

Building and Operating the LHeC

Appendix 2

Scientific Advisory Committee

List of Participants and Institutes