Electron-Nucleon Scattering at the Tera Scale

CERN-ECFA-NuPECC: Preparing a Conceptual Design Report on the LHeC

Large Hadron Electron Collider
Progress Report to ECFA

Max Klein
for the LHeC Group

ECFA at CERN Geneva 27. November 2009

www.lhec.cern.ch
Kinematics and Recent Developments

2008

September  Divonne workshop; NuPECC Meeting at Glasgow
October  ICFA Seminar at SLAC
November  ECFA Plenary at CERN
December  Convenor’s Meeting at CERN

2009

March  Visit to SLAC [Linac]
April  PAC09 at Vancouver - Papers, Talk, Proceedings
May  Visit to BINP Novosibirsk [Ring Magnets]
June  Low x / HPD meeting at CERN, pre-Blois
September  Divonne II (CERN-ECFA-NuPECC Workshop)
           ~80 talks from ~ 100 participants
October  NuPECC Long Range Planning Workshop
Conceptual Design Report
Large Hadron Electron Collider (LHeC) at CERN

DRAFT - February 2009

Extended version by Mid December09

1. Introduction

2. Particle Physics and Deep Inelastic Lepton-Nucleon Scattering
   1. DIS from 1 to 100 GeV
   2. Status of the Exploration of Nucleon Structure
   3. Tera Scale Physics

3. The Physics Programme of the LHeC
   1. New Physics at Large Scales
   2. Precision QCD and Electroweak Physics
   3. Physics at High Parton Densities

4. Design Considerations
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   3. Compatibility with the LHC
   4. Proton, Deuteron and Ion Beams

5. A Ring-Ring Collider Concept
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   2. Lepton Ring
   3. Synchrotron Radiation
   4. Interaction Region
   5. Installation
   6. Infrastructure and Cost

6. A Linac-Ring Collider Concept
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   2. Linac
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7. A Detector for the LHeC
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   1. Physics Highlights
   2. Parameters
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Appendix

1. Tasks for a TDR
2. Building and Operating the LHeC
Physics Programme of the LHeC

+ Unfolding completely the parton structure of the proton (and of the neutron and photon) and search for sub-substructure down to $6 \times 10^{-20}$m

+ Exploration of new symmetries and the grand unification of particle interactions with electroweak and strong interaction measurements of unprecedented precision.

+ Search for and exploration of new, Terascale physics, in particular for new states with lepton qu.numbers (RPV SUSY, LQ, excited fermions), complementary to the LHC

+ Exploration of high density matter [low x physics beyond the expected unitarity limit for the growth of the nucleon gluon density]

+ Unfolding the substructure and parton dynamics inside nuclei by an extension of the kinematic range by four orders of magnitude [initial state of the QGP]

Large amount of studies done and ongoing, without aiming at complete list. Follows an example per point each. Note that these are final when written up.
Strange and Anti-Strange Quark Distributions

Not measured with H1,ZEUS HERMES (N_{K}): s much larger?
Dimuon data: s ≠ sbar?

W,Z sensitive to s

LHeC: measure both strange and anti-s with high precision for the first time

\[ W^- sbar \rightarrow cbar \]

1 fb^{-1}
\[ \varepsilon_s = 0.1 \]
\[ \varepsilon_q = 0.01 \]
\[ \delta_{\text{sys}} = 0.1 \]
\[ -\theta_h \geq 1^\circ \]
\[ -\theta_h \geq 10^\circ \]

\[ Q^2 \approx 1 \text{ GeV}^2 \]
High Precision Electroweak Physics

Precision measurement of weak neutral current couplings (+pdf’s): access to new electroweak physics.

40 TeV limits on Contact Interactions and correspondingly on extra dimensions
Gluon - SM Higgs

In SM Higgs production is gluon dominated

LHeC: huge $x, Q^2$ range for $xg$ determination

WW to Higgs fusion has sizeable ep $\sigma$ xsection

Cf Divonne 09 for QCD bgd studies + btagging
In MSSM Higgs production is $b$ dominated

First measurement of $b$ at HERA can be turned to precision measurement.

LHeC: higher fraction of $b$, larger range, smaller beam spot, better Si detectors
Discovery of Parton Saturation – ep, low x

Full simulation of $F_2$ and $F_L$
Both together must reveal saturation
Nuclear Structure and Dynamics

Extension of $Q^2$, $1/x$ range by $10^4$

Fermi motion -- $p$ tagging
Shadowing -- diffraction

$p$, $D$, $Ca$, $Pb$ beams

Complete determination of nPDFs into nonlinear regime
LHeC is bound to discover parton saturation in $eA$ AND $ep$
Accelerator and Detector Design

Collaborations of CERN
with experts from Cockcroft, BNL, DESY, KEK Lausanne, Novosibirsk, SLAC, TAC

20 workpackages with identified responsibilities
Ring-Ring ep/eA

$E_e = 10 \ldots 70$ GeV. $L_{ep} \sim 10^{33}$ cm$^{-2}$s$^{-1}$ (100 times HERA)

Injector: dedicated or SPL based.

Detailed first design study in JINST P1001 (2006)
**RR Luminosity and Parameters**

**Luminosity for e⁺p safely above \(10^{33}\text{cm}^{-2}\text{s}^{-1}\)**

Used “ultimate” LHC beam parameters

Energy limited by injection and syn.rad losses

Power limit set to 100 MW

Small p tuneshift: simultaneous pp and ep

\[
L = \frac{N_{p}^{\gamma}}{4\pi e e_{p} e_{n}} \cdot \frac{I_{e}}{\sqrt{\beta_{px} \beta_{py}}} = 8.310^{32} \cdot \frac{I_{e}}{50\text{mA}} \cdot \frac{m}{\sqrt{\beta_{px} \beta_{py}}} \cdot \text{cm}^{-2} \text{s}^{-1}
\]

\[
I_{e} = 0.35\text{mA} \cdot \frac{P}{\text{MW}} \left(\frac{100\text{GeV}}{E_{e}}\right)^{4}
\]

<table>
<thead>
<tr>
<th>Ultimate Parameter</th>
<th>Protons</th>
<th>Electrons</th>
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<tbody>
<tr>
<td>(N_{p}=1.7\times10^{11})</td>
<td>(N_{e}=1.4\times10^{10})</td>
<td>nb=2808</td>
</tr>
<tr>
<td>(I_{p}=860\text{mA})</td>
<td>(I_{e}=71\text{mA})</td>
<td></td>
</tr>
<tr>
<td><strong>Optics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\beta_{xp}=230\text{ cm})</td>
<td>(\beta_{xe}=12.7\text{ cm})</td>
<td></td>
</tr>
<tr>
<td>(\beta_{yp}=60\text{ cm})</td>
<td>(\beta_{ye}=7.1\text{ cm})</td>
<td></td>
</tr>
<tr>
<td>(\alpha_{xp}=0.5\text{ nm rad})</td>
<td>(\alpha_{xe}=9\text{ nm rad})</td>
<td></td>
</tr>
<tr>
<td>(\alpha_{yp}=0.5\text{ nm rad})</td>
<td>(\alpha_{ye}=4\text{ nm rad})</td>
<td></td>
</tr>
<tr>
<td><strong>Beamsize</strong></td>
<td>(\sigma_{x}=34\mu\text{m})</td>
<td>(\sigma_{y}=17\mu\text{m})</td>
</tr>
<tr>
<td><strong>Tuneshift</strong></td>
<td>(\Delta x=0.00061)</td>
<td>(\Delta x=0.056)</td>
</tr>
<tr>
<td></td>
<td>(\Delta y=0.00032)</td>
<td>(\Delta y=0.062)</td>
</tr>
<tr>
<td><strong>Luminosity</strong></td>
<td>(L=1.03\times10^{33})</td>
<td></td>
</tr>
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</table>
Optics in the arcs

2009: optimisation of FODO cell
- Dispersion reduced to 20-50cm
- Emittance $\varepsilon_x = 7.5$ nm, $\varepsilon_y = 3.7$ nm

**MEDIUM** or **WEAK BEND SOLUTION**

- $\beta_x = 7.1$ cm, $\beta_y = 12.7$ cm

- "inner" triplet focus

**Mini beta design**

**Optimisation ongoing**
Dipole Magnets

O-shaped magnet with ferrite core [BINP-CERN]

Prototype design under way at Novosibirsk, May 2010

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>LEP</th>
<th>LHeC</th>
</tr>
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<tbody>
<tr>
<td>Cross Section/ cm²</td>
<td>50 x 50</td>
<td>20 x 10</td>
</tr>
<tr>
<td>Magnetic field/ T</td>
<td>0.02-0.11</td>
<td>0.02-0.135</td>
</tr>
<tr>
<td>Energy Range/GeV</td>
<td>20-100</td>
<td>10-70</td>
</tr>
<tr>
<td>Good Field Area/cm²</td>
<td>5.9 x 5.9</td>
<td>6 x 3.8</td>
</tr>
<tr>
<td>FODO length/m</td>
<td>76</td>
<td>53</td>
</tr>
<tr>
<td>Magnet length/m</td>
<td>2 x 34.5</td>
<td>2 x 14.76</td>
</tr>
<tr>
<td>segmentation</td>
<td>6 cores</td>
<td>14</td>
</tr>
<tr>
<td>Number of magnets</td>
<td>736</td>
<td>488</td>
</tr>
<tr>
<td>Weight/ kg/m</td>
<td>800</td>
<td>240</td>
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</table>
Ring – Work in progress

Interaction region design

Installation study

Systematic investigation of clashes with LHC installation and possible ways ‘around’

Installation sequence - timeline

Polarisation
Two LINAC Configurations [CERN-SLAC]

Arc Radius = 120 m

Length = 1.5 + 4*.12 + 0.3 (IR?) = 2.3 km

Arc Radius = 700 m

Length = 3.9 + 0.3 + 0.3 (IR?) = 4.5 km

60 GeV
31 MV/m, pulsed two passes

60 GeV
13 MV/m CW ERL
4 passes

140 GeV
31 MV/m, pulsed 2 passes
## LINAC-Ring Parameters

<table>
<thead>
<tr>
<th>Configuration</th>
<th>60 GeV, pulsed</th>
<th>60 GeV CW ERL</th>
<th>140 GeV pulsed</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_e/\text{bunch}/10^9/50\text{ns} )</td>
<td>4</td>
<td>1.9</td>
<td>2</td>
</tr>
<tr>
<td>gradient MV/m</td>
<td>32</td>
<td>13</td>
<td>32</td>
</tr>
<tr>
<td>normalised ( \varepsilon/\mu m )</td>
<td>50</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>cryo power/MW</td>
<td>3</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td>effective beam power/MW</td>
<td>50</td>
<td>40/(1-( \eta_{\text{ERL}} ))</td>
<td>50</td>
</tr>
</tbody>
</table>

### Luminosity for ultimate beam

\[
N_p = 1.7 \cdot 10^{11}, \varepsilon_p = 3.8 \mu m, \beta^* = 0.2 m, \gamma = 7000/0.94
\]

\[
L = 8 \cdot 10^{31} \text{cm}^{-2}s^{-1} \cdot \frac{N_p \cdot 10^{-11}}{1.7} \cdot \frac{0.2 \cdot P/\text{MW}}{\beta^* / m} \cdot \frac{E_e / \text{GeV}}{E_e / \text{GeV}}
\]

An Electron-Proton Collider in the TeV Range

M. Tigner, Cornell Univ., Ithaca, NY

B. Wilk, F. Willeke. DESY, Hamburg, FRG

As the era of e-p colliders begins we need to begin a search for practical schemes for increasing the available center of mass energies. The use of an SC linac on SC proton ring approach may offer a practical possibility while maintaining a favorable electron to proton beam energy ratio.

The LR combination yet requires a still better p beam or/and \( E_e \) recovery to come to luminosity beyond \( 10^{32}\text{cm}^{-2}s^{-1} \)
e Optics for LINAC

from injector
Linac (500 MeV)

2 passes

4 passes - ERL
LINAC - Work in Progress

IR Options:
Head on $\rightarrow$ dipoles
Crossing $\rightarrow$ like RR IR

Positron source

Difficult to reach high intensity. Perhaps best suited: hybrid target production of unpolarised positrons. Several stations? cf Divonne
Muon chambers
(fwd,bwd,central)

**Coil (r=3m l=11.8m, 3.5T)**
[Return Fe not drawn,
2 coils w/o return Fe studied]

**Central Detector**

**Pixels**
Elliptic beam pipe (~3cm - or smaller)

**Silicon (fwd/bwd+central)**
[Strip or/and Gas on Slimmed Si Pixels]
[0.6m radius for 0.03% * pt in 3.5T field]

El.magn. Calo (Pb,Scint. 9-12X0)
Hadronic Calo (Fe/LAr; Cu/Brass-Scint. ~30λ)

**Fwd Detectors**
(down to 1°)

**Silicon Tracker**
[Pix/Strip/Strixel/Pad Silicon or/and Gas on Slimmed Si Pixels]

Calice (W/Si); dual ReadOut - Elm Calo
FwdHadrCalo:
Cu/Brass-Scintillator

**Bwd Detectors**
(down to 179°)

**Silicon Tracker**
[Pix/Strip/Strixel/Pad Silicon or/and Gas on Slimmed Si Pixels]
Cu/Brass-Scintillator,
Pb-Scintillator (SpaCal - hadr, elm)

Extensions in fwd direction (tag p,n,d) and backwards (e,y) under study.
Completion of the CDR

Steps to go in 2010

1. Finalise physics and technical studies
2. DIS10 Firenze [April] and IPACC Japan [May]
3. Draft CDR June 2010
4. Divonne III – Updates and Discussion with referees
5. November 10: Final report to ECFA
6. Submit CDR to CERN, ECFA, NuPECC

LHeC relies on expertise and enthusiasm of many colleagues and support by ECFA, NuPECC and CERN

LHeC barack 561
Backup slides
Quark-Gluon Dynamics - Diffraction and HFS (fwd jets)

Diffraction to accompany (SUSY) Higgs fwd physics at LHC

Understand multi-jet emission (uninteg. pdf’s), tune MC’s
At HERA resolved γ effects mimic non-kt ordered emission
Crucial measurements for QCD, and for QCD at the LHC

P.Newman, DIS07

H.Jung, L.Loennblad, THERA study
Determination of LQ properties in single production: e.g. Fermion Number

In pp: look at signal separately when resonance is formed by \((e^+ + \text{jet})\) and \((e^- + \text{jet})\):

\[
\begin{align*}
\text{g} & \quad \text{F}=0 & \text{q} & \quad \text{e}^+ \\
\lambda & \quad \text{q} & \quad \text{e}^- \\
\text{g} & \quad \text{F}=0 & \bar{\text{q}} & \quad \text{e}^-
\end{align*}
\]

\[
\sigma(e^+_{\text{out}}) > \sigma(e^-_{\text{out}})
\]

for \(F=0\)

Sign of the asymmetry gives \(F\), but could be statistically limited at LHC. (*)

Easier in ep ! Just look at the signal with incident \(e^+\) and incident \(e^-\), build the asymmetry between \(\sigma(e^+_{\text{in}})\) and \(\sigma(e^-_{\text{in}})\).

If LHC observes a LQ-like resonance, \(M < 1 - 1.5\) TeV, LHeC could determine \(F\) if \(\lambda\) not too small.

\[(*)\] First rough study done for the 2006 paper. Need to check / refine with a full analysis of signal and backgrounds.
Quark-Gluon Dynamics (saturation, GPDs) - ep

\[ xG(x) = \frac{dN_g}{dy} \]

\[ xG(x) \sim x^\lambda \]

BFKL

SATURATION

REGGE

DATA

\[ Q^2 = 30 \text{ GeV}^2 \text{ (stat errors only)} \]

- LHeC sim (FS04sat, 1 fb\(^{-1}\))
- LHeC sim (CGC, 1 fb\(^{-1}\))

LHeC opens phase space to discover saturation in DIS

J. Bartels at Divonne on low \( x \) theory

High luminosity, polarisation, accuracy for GPD’s (DVCS)

LHeCsat data in NNPDF1.0

Divonne 08
**Strong Coupling Constant**

Simulation of $\alpha_s$ measurement at LHeC

$\alpha_s$ least known of coupling constants
Grand Unification predictions suffer from $\delta\alpha_s$

DIS tends to be lower than world average

LHeC: per mille accuracy indep. of BCDMS.
Challenge to experiment and to h.o. QCD

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**DATA**

<table>
<thead>
<tr>
<th>Description</th>
<th>$\text{exp. error on } \alpha_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC e+ only</td>
<td>0.48%</td>
</tr>
<tr>
<td>NC</td>
<td>0.41%</td>
</tr>
<tr>
<td><strong>NC &amp; CC</strong></td>
<td><strong>0.23% :=(1)</strong></td>
</tr>
<tr>
<td>$\gamma_{h}&gt;5^\circ$</td>
<td>0.36% :=(2)</td>
</tr>
<tr>
<td>+BCDMS</td>
<td>0.22%</td>
</tr>
<tr>
<td>+BCDMS</td>
<td>0.22%</td>
</tr>
<tr>
<td>stat. *=2</td>
<td>0.35%</td>
</tr>
</tbody>
</table>

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Blumlein et al '06
New Physics in the eq Sector

Exact knowledge of pdf’s may be crucial to understand CI’s