A Large Hadron electron Collider at the LHC

40-140 GeV on 1-7 TeV $e^\pm p$, also $eA$

Progress since DIS07 and News from DIS08
(based on Summary by Max Klein at DIS 2008 at UCL, London, UK)

On November 30th, 2007, ECFA unanimously endorsed the proposal to work out a Conceptual Design Report for the LHeC, supported by CERN. NuPECC has formed a study group to investigate the prospects for the LHeC in Europe and the EIC in the United States as part of the long range planning for European Nuclear Physics.

Swapan Chattopadhyay
Cockcroft Institute, UK
on behalf of the LHeC Collaboration
The LHeC is a PeV equivalent fixed target ep scattering experiment, at 50 000 times higher energy than the pioneering SLAC MIT experiment. It may need a LINAC not much longer than the 2mile LINAC to the right. Its physics potential is extremely rich.
Physics and Range

High mass 1-2 TeV
$r_q$ few times $10^{-20}$ m

High precision partons in plateau of the LHC

Large $x$

3 physics subjects:
New Physics
QCD+electroweak
High parton densities

Former considerations:
ECFA Study 84-10
J.Feltesse, R.Rueckl: Aachen Workshop (1990)
The THERA Book (2001) & Part IV of TESLA TDR
Ring-Ring LHeC Interaction Region Design

Table 3: Main Parameters of the Lepton-Proton Collider

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Leptons</th>
<th>Protons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energies</td>
<td>GeV</td>
<td>70</td>
<td>7000</td>
</tr>
<tr>
<td>Total Beam Current</td>
<td>mA</td>
<td>74</td>
<td>544</td>
</tr>
<tr>
<td>Number of Particles / bunch</td>
<td>(10^{10})</td>
<td>1.04</td>
<td>17.0</td>
</tr>
<tr>
<td>Horizontal Beam Emittance</td>
<td>nm</td>
<td>7.6</td>
<td>0.501</td>
</tr>
<tr>
<td>Vertical Beam Emittance</td>
<td>nm</td>
<td>3.8</td>
<td>0.501</td>
</tr>
<tr>
<td>Horizontal (\beta)-functions at IP</td>
<td>cm</td>
<td>12.7</td>
<td>180</td>
</tr>
<tr>
<td>Vertical (\beta)-function at the IP</td>
<td>cm</td>
<td>7.1</td>
<td>50</td>
</tr>
<tr>
<td>Energy loss per turn</td>
<td>GeV</td>
<td>0.707</td>
<td>6 (\cdot 10^{-6})</td>
</tr>
<tr>
<td>Radiated Energy</td>
<td>MW</td>
<td>50</td>
<td>0.003</td>
</tr>
<tr>
<td>Bunch frequency / bunch spacing</td>
<td>MHz / ns</td>
<td>40 / 25</td>
<td></td>
</tr>
<tr>
<td>Center of Mass Energy</td>
<td>GeV</td>
<td>1400</td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>(10^{32}) cm(^{-2})s(^{-1})</td>
<td>1.1</td>
<td></td>
</tr>
</tbody>
</table>

J.Dainton et al, JINST 1 P10001 (2006)

foresees simultaneous operation of pp and ep
Design Details

Synchrotron radiation fan and HERA type absorber

First p beam lens: septum quadrupole.
Cross section and Field calculation

9.1kW

$E_{\text{crit}} = 76\text{keV}$

100W/mm$^2$

cf also W. Bartel
Aachen 1990
Accelerator (RR) questions considered

Power: 25ns: nx40MHz rf frequency. Imax 100 mA: 60 klystrons with 1.3MW coupler of perhaps 0.5MW, 66% efficient… need space for rf in bypasses

Injection: LEP2 was N= 4 \times 10^{11} in 4 bunches, LHeC is 1.4 \times 10^{10} in 2800 bunches may inject at less than 20 GeV. Injection is no principal problem regarding power and technology (ELFE, KEK, direct?)

Synchrotron load to LHC magnets: can be shielded (water cooled Pb)

Bypasses: for ATLAS and CMS but also for further Pi. l~500m start in the arcs. May ensure same length of e ring as p with ~ -20cm radius of e ring.

Space: first look at the installation on top of LHC
Luminosity: Ring-Ring

\[ L = \frac{N_p\gamma}{4\pi e \varepsilon_{pn}} \cdot \frac{I_e}{\sqrt{\beta_{px}\beta_{py}}} = 8.310^{32} \cdot \frac{I_e}{50mA} \cdot \frac{m}{\sqrt{\beta_{px}\beta_{pn}}} \ cm^{-2} s^{-1} \]

\[ I_e = 0.35mA \cdot \frac{P}{MW} \cdot \left( \frac{100GeV}{E_e} \right)^4 \]

\[ \varepsilon_{pn} = 3.8\mu m \]
\[ N_p = 1.7 \cdot 10^{11} \]
\[ \sigma_{p(x,y)} = \sigma_{e(x,y)} \]
\[ \beta_{px} = 1.8m \]
\[ \beta_{py} = 0.5m \]

10^{33} can be reached in RR
E_e = 40-80 GeV & P = 5-60 MW.

HERA was 1-4 \times 10^{31} \ cm^{-2} \ s^{-1} huge gain with SLHC p beam

F.Willeke in hep-ex/0603016:
Design of interaction region
for 10^{33} : 50 MW, 70 GeV

Factor of 5 possible to gain with intensity and beam emittance (cf H.Braun this workshop).
May relax power requirement.
about 20 GeV injection energy

be able to fill reasonably fast - say within 10 min
low intensity $1.4 \times 10^{10}$ / bunch - could do without accumulation

many (2800) bunches, 25 ns spacing, total intensity $3.92 \times 10^{13}$ el

injection scheduling:
analog to protons (3 - 4 batches of nominally 72 bunches)

---

**LHeC injector**

$f_{rf} \sim 1$ GHz, gradient 31.5 MV/m
Linac $L = 150$ m 7x shorter

$V_{rf} = 4$ GV, 5 passes; last 16 GeV

$q = (16/21.5)^{4} \times 56.9$ m = 17.5 m
or 3.3x shorter

significantly downscaled $L \approx 600$ m
and simplified (5 passes) version of ELFE@CERN

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**what about CLIC** [clicetable2007.html]

high gradient 100 MV/m in 85% of LINAC; $L = 235$ m to reach 20 GeV

$N = 3.72e9$ / bun; $k = 312$ bun/train; Linac repetition rate of 50 Hz: 5.83e13 Elec/sec.

Significant overhead for drive beam generation - probably not very
economic for a relatively short LINAC.

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**20 GeV SC linac, inspired by ILC**

gradient 31.5 MV/m (ILC BCD) in 85% of LINAC: $L = 747$ m

$N = 2e10$ / bun, $k = 2820$ bun/train; repetition rate of 5 Hz: 2.82e14 Elec/secs

modify to match LHC batch structure

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more cost effective (?) than single LINAC
+ extra phys. potential

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H.Burkhardt DIS08
Bypass Layout Study - based on LEP lattice - no extra bends

schematic layout
Dainton / Willeke et al.

LEP lattice

<table>
<thead>
<tr>
<th>Point</th>
<th>*</th>
<th>*</th>
<th>s IP5, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>QD24.L5</td>
<td>0.1100390391</td>
<td>0.0113064017</td>
<td>677.879431</td>
</tr>
<tr>
<td>QF23.L5</td>
<td>0.09873263743</td>
<td>0.0113064017</td>
<td>638.379431</td>
</tr>
<tr>
<td>QD22.L5</td>
<td>0.08742623577</td>
<td>0.0113064017</td>
<td>598.879431</td>
</tr>
<tr>
<td>QF21.L5</td>
<td>0.07611983411</td>
<td>0.0113064017</td>
<td>559.379431</td>
</tr>
<tr>
<td>QD20.L5</td>
<td>0.06481343245</td>
<td>0.0113064017</td>
<td>519.879431</td>
</tr>
<tr>
<td>QF19.L5</td>
<td>0.0535070308</td>
<td>0.0113064017</td>
<td>480.379431</td>
</tr>
<tr>
<td>QL18.L5</td>
<td>0.04220062914</td>
<td>0.0113064017</td>
<td>440.479431</td>
</tr>
<tr>
<td>QL17.L5</td>
<td>0.03843462774</td>
<td>0.0037660014</td>
<td>408.049431</td>
</tr>
<tr>
<td>QL16.L5</td>
<td>0.03089842621</td>
<td>0.0075362015</td>
<td>380.979431</td>
</tr>
<tr>
<td>QL15.L5</td>
<td>0.02336222468</td>
<td>0.0075362015</td>
<td>353.909431</td>
</tr>
<tr>
<td>QL14.L5</td>
<td>0.01582602315</td>
<td>0.0075362015</td>
<td>326.839431</td>
</tr>
<tr>
<td>QL13.L5</td>
<td>0.008289821623</td>
<td>0.0075362015</td>
<td>299.769431</td>
</tr>
<tr>
<td>QL12.L5</td>
<td>0.0007536200942</td>
<td>0.0075362015</td>
<td>272.699431</td>
</tr>
<tr>
<td>QL11.L5</td>
<td>0.0</td>
<td>0.0007536201</td>
<td>245.629431</td>
</tr>
</tbody>
</table>
Luminosity: Linac-Ring

\[ L = \frac{N_p \gamma}{4 \pi \varepsilon_{pn} \beta^*} \cdot \frac{P}{E_e} = 1 \times 10^{32} \cdot \frac{P}{MW} \cdot \frac{E_e}{GeV} \cdot \frac{cm^{-2} s^{-1}}{P/ MW} \]

2 \(10^{32}\) may be reached with LR:
- \(E_e = 40-140\) GeV & \(P=20-60\) MW
- LR: average lumi close to peak!
- \(\rightarrow\) 10 times HERA II luminosity.

LINAC is not physics limited in energy, but cost + power limited.
- 140 GeV at 23 MV/m: 6km + gaps

New p injector chain, LHC Luminosity Upgrade.

Note: positron source challenge:
- SLC \(10^{13}\) /sec
- ILC \(10^{14}\) /sec
- LHeC at \(10^{32}\) needs \(10^{15}\) /sec

DIS08, H.Braun
Recirculated superconducting c.w. Linac for LHeC

Tentative parameter set for $10^{33}$cm$^{-2}$s$^{-1}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$</td>
<td>70 GeV</td>
</tr>
<tr>
<td>$E_{\text{injector}}$</td>
<td>1 GeV</td>
</tr>
<tr>
<td>$I_{\text{Beam}}$</td>
<td>1.2 mA</td>
</tr>
<tr>
<td>$N_B$</td>
<td>$1.87 \times 10^8$</td>
</tr>
<tr>
<td>Bunch spacing*</td>
<td>25 ns</td>
</tr>
<tr>
<td>$P_{\text{Beam}}$</td>
<td>84 MW</td>
</tr>
<tr>
<td>$P_{\text{SR}}$</td>
<td>5.6 MW</td>
</tr>
<tr>
<td>$N_{\text{Recirculation}}$</td>
<td>6</td>
</tr>
<tr>
<td>$V_{\text{Linac}}$</td>
<td>$2 \times 6.14$ GeV</td>
</tr>
<tr>
<td>$L_{\text{Linac}}$</td>
<td>$2 \times 750$ m</td>
</tr>
<tr>
<td>$L_{\text{Arc}}$</td>
<td>$500 \pi$</td>
</tr>
<tr>
<td>$L_{\text{Tunnel}}$</td>
<td>$\approx 5$ km</td>
</tr>
<tr>
<td>$G$</td>
<td>12 MV/m</td>
</tr>
<tr>
<td>$P_{\text{AC RF plant}}$</td>
<td>236 MW</td>
</tr>
<tr>
<td>$P_{\text{AC cryogenic plant}}$</td>
<td>29 MW</td>
</tr>
<tr>
<td>$P_{\text{Beam}}/P_{\text{AC}}$</td>
<td>32%</td>
</tr>
</tbody>
</table>

*here an uniform filling of LHC with proton bunches is assumed. Still needs to be adapted to real filling pattern.
Can this be combined with energy recovery scheme to reduce RF power and beam dump requirements?

Not easily, because of energy imbalance due to SR losses but this needs further studies.
## Parameters for pulsed Linacs for 140 GeV, $10^{32} \text{cm}^{-2}\text{s}^{-1}$

<table>
<thead>
<tr>
<th></th>
<th>SC technology</th>
<th>NC technology</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>X FEL</strong> <strong>20 GeV</strong></td>
<td>X FEL 20 GeV</td>
<td>X FEL 20 GeV</td>
</tr>
<tr>
<td><strong>LHeC</strong> <strong>140 GeV, $10^{32} \text{cm}^{-2}\text{s}^{-1}$</strong></td>
<td>LHeC 140 GeV, $10^{32} \text{cm}^{-2}\text{s}^{-1}$</td>
<td>LHeC 140 GeV, $10^{32} \text{cm}^{-2}\text{s}^{-1}$</td>
</tr>
<tr>
<td>$I_{\text{Beam}}$ during pulse</td>
<td>5 mA</td>
<td>11.4 mA</td>
</tr>
<tr>
<td>$N_E$</td>
<td>$0.624 \cdot 10^{10}$</td>
<td>$5.79 \cdot 10^{10}$</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>0.2 μs</td>
<td>0.8 μs</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>0.65 ms</td>
<td>1.0 ms</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>10 Hz</td>
<td>10 Hz</td>
</tr>
<tr>
<td>G</td>
<td>23.6 MV/m</td>
<td>23.6 MV/m</td>
</tr>
<tr>
<td>Total Length</td>
<td>1.27 km</td>
<td>8.72 km</td>
</tr>
<tr>
<td>$P_{\text{Beam}}$</td>
<td>0.65 MW</td>
<td>16.8 MW</td>
</tr>
<tr>
<td>Grid power for RF plant</td>
<td>4 MW</td>
<td>59 MW</td>
</tr>
<tr>
<td>Grid power for Cryoplant</td>
<td>3 MW</td>
<td>20 MW</td>
</tr>
<tr>
<td>$P_{\text{Beam}}/P_{\text{AC}}$</td>
<td>10%</td>
<td>21%</td>
</tr>
</tbody>
</table>

H. Braun, this workshop
H. Braun, this workshop

M. Tigner,
Can tunnel for LHeC Linac be build as first part of a LC tunnel at CERN?

Tunnel studies for CLIC and ILC at CERN both have tunnels which are deeper underground than LHC and seen from top they both pass close to LHC ring center. Therefore they are not suited to send e⁻ beam tangential to LHC ring.
Strong Coupling

Detector Requirements

- Largest possible acceptance
  - 1-179°
  - 7-177°

- High resolution tracking
  - 0.1 mrad
  - 0.2-1 mrad

- Precision electromagnetic calorimetry
  - 0.1%
  - 0.2-0.5%

- Precision hadronic calorimetry
  - 0.5%
  - 1%

- High precision luminosity measurement
  - 0.5%
  - 1%

- LHeC
  - HERA

extended kinematic range uncertainties 1/2 of H1

Exp + Thy challenge N³LO

T. Kluge, MK, DIS08
CI and Leptoquarks

VV model (conserving parity)

AAD model (Large Extra Dimensions)

Similar limits for $M_S$

A.Zarnecki DIS08
Quantum Numbers

Charge asymmetry much cleaner in ep than in pp. Similar for simultaneous determination of coupling and quark flavour.

E.Perez, DIS07

Scalar LQ, $\lambda=0.1$, single production

Fermion number determination

LHeC, 1 fb$^{-1}$

$E_e = 140$ GeV

LHC, 100 fb$^{-1}$

$E_e = 140$ GeV

Scalar LQ

$\lambda = 0.3$
A new level of quark distribution measurements
unfolding and parton amplitudes (GPDs)

$\bar{u}(x) \neq \bar{d}(x)$
$\bar{s}(x) \neq s(x)$

d/u at low x from deuterons

Strange & Antistrange from CC

Shadowing related to diffraction
SB’s non intrinsic wishlist for the LHeC

- Inclusive Higgs
- Diffractive Higgs
- Higgs ttbar

Kopeliovich, Schmidt, sjb
Gluon

(a) $LHC, \sqrt{s} = 14$ TeV, SM

- $\sigma (pb)$ vs $M_H$ (GeV)
- $gg\rightarrow H$
- $bb\rightarrow H$

Higgs

- MSSM

Beauty

(b) $LHC, \sqrt{s} = 14$ TeV, MSSM, $\tan\beta=10$

- $\sigma (pb)$ vs $M_A$ (GeV)
- $gg\rightarrow A$
- $bb\rightarrow A$

$xg$

$x^2 = 10000$ GeV$^2$

- CTEQ 6.1
- LHeC simulation, 10 fb$^{-1}$

$F_2$ vs $x$ vs $Q^2/GeV^2$

- HERA
- $x=0.007$
- $x=0.03$
- $x=0.07$

23rd May 2008 Swapan Chattopadhyay Presentation to The 4th Electron Ion Collider Workshop, Hampton University
May not be able to simultaneously fit the two proton structure functions $F_2$ and $F_L$ when these represent a saturation CDM with enlarged energy, saturation scale moves into DIS region and DGLAP may truly be shown to fail when confronted with very low $x$ data.

$F_L$ takes long (1986-2008)…
Measurement of nuclear parton distributions
Non-linear effects (xg 'beyond' unitarity)
50% diffraction ..

NuPECC study group
Tullio Bressani, INFN, Torino Univ.
Jens Jørgen Gaardhøje, Niels Bohr Inst.
Günther Rosner, Glasgow Univ. (chair)
Hans Stroher, FZ Juelich

This workshop: cf M.Lamont
The Goal of the ECFA-CERN Workshop(s) is a CDR by 2009/2010.

Accelerator Design [RR and LR]
Closer evaluation of technical realisation: injection, magnets, rf, power efficiency, cavities, ERL…
What are the relative merits of LR and RR? Recommendation. Workpackages

Interaction Region and Forward/Backward Detectors

Design of IR (LR and RR), integration of fwd/bwd detectors into beam line.

Infrastructure
Definition of infrastructure - for LR and RR.

Detector Design
A conceptual layout, including alternatives, and its performance [ep and eA].

New Physics at Large Scales
Investigation of the discovery potential for new physics and its relation to the LHC and ILC/CLIC.

Precision QCD and Electroweak Interactions
Quark-gluon dynamics and precision electroweak measurements at the TERA scale.

Physics at High Parton Densities [small x and eA]
QCD and Unitarity, QGP and the relations to nuclear, pA/AA LHC and SHEν physics.

Divonne, 1.-3.9.08
ECFA CERN Workshop at Divonne 1.-3.9.2008

http://www.lhec.org.uk

Opening

J. Engelen (CERN)
K. Meier (ECFA)
G. Altarelli (Roma):
DIS in the LHC time

1.9. 2pm

Indico=31463

Email:
event-lhec-workshop@cern.ch

Patricia Mage-Granados
Jill Karlson Forestier
Urs Wiedemann
Max Klein

Scientific Advisory Committee

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Allen Caldwell (MPI Munich)
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Steven Vigdor (BNL)
Ferdinand Willeke (BNL)
Frank Wilczek (MIT)

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Max Klein - chair (Liverpool)
Paul Newman (Birmingham)
Emmanuelle Perez (CERN)
Wesley Smith (Wisconsin)
Bernd Surrow (MIT)
Katsuo Tekeshuku (KEK)
Urs Wiedemann (CERN)

Registration is open

http://indico.cern.ch/event/LHeC_workshop
Concluding Remarks

The LHeC has survived expert scrutiny and gets momentum in terms of accelerator concepts, next EPAC Genoa June 2008

ECFA and CERN have expressed an interest in a Conceptual Design Report for the LHeC by 2009/10. An organisational structure has been put in place which will allow further developments of the machine, IR, detector and physics ideas. A technical design may follow if appropriate.

NuPECC has been made aware of the developments and joint discussions and developments beginning to emerge.

The LHeC requires the LHC to be a success and the CERN accelerator complex to function and be upgraded. It will have to attract world wide efforts for becoming realised while the pp LHC operation is still ongoing.

The physics will be worked out and emphasis will be given to the complementarity with the LHC and also ILC/CLIC.

Deep Inelastic Scattering in the LHC time may become reality.
ECFA CERN Workshop Convenors

Accelerator Design [RR and LR]
Oliver Bruening (CERN), John Dainton (Cockcroft/Liverpool)

Interaction Region and Forward/Backward Detectors
Bernhard Holzer (DESY), Uwe Schneeekloth (DESY), MM (tbc)

Infrastructure
John Osborne (CERN)

Detector Design
Peter Kostka (DESY), Rainer Wallny (UCLA), Alessandro Polini (Bologna)

New Physics at Large Scales
Emmanuelle Perez (CERN), Georg Weiglein (Durham)

Precision QCD and Electroweak Interactions
Olaf Behnke (DESY), Paolo Gambino (Torino), Thomas Gehrmann (Zuerich)

Physics at High Parton Densities [small x and eA]
Nestor Armesto (CERN), Brian Cole (Columbia), Paul Newman (B’ham), Anna Stasto (MSU)

Many thanks to many people

http://www.lhec.org.uk
Summary and Proposal to ECFA

As an add-on to the LHC, the LHeC delivers in excess of 1 TeV to the electron-quark cms system. It accesses high parton densities ‘beyond’ what is expected to be the unitarity limit. Its physics is thus fundamental and deserves to be further worked out, also with respect to the findings at the LHC and the final results of the Tevatron and of HERA.

First considerations of a ring-ring and a linac-ring accelerator layout lead to an unprecedented combination of energy and luminosity in lepton-hadron physics, exploiting the latest developments in accelerator and detector technology.

It is thus proposed to hold two workshops (2008 and 2009), under the auspices of ECFA and CERN, with the goal of having a Conceptual Design Report on the accelerator, the experiment and the physics. A Technical Design report will then follow if appropriate.