A Large Hadron - electron Collider

on behalf of LHeC working group and High Parton Density/low-x WG conveners:

N. Armesto, B. Cole, P. Newman, A. Stasto

Brian A Cole
Columbia University
LHeC Scope

electrons (and positions ?) with polarization:
  maximum energy 50-150 GeV

on protons:
  maximum energy 7 Tev (?)

on nuclei:
  maximum energy 2.75 TeV / A for Pb

on deuterons:
  maximum energy 3.5 TeV / A

- See www.lhec.org.uk
LHeC Physics Program

• Precision standard model measurements
  – Precision $\alpha_s$, effective couplings, flavor dependence
  – Precision Higgs measurements

• Beyond SM physics
  – Lepto-quarks, contact interactions, excited fermions
  – R-parity violating SUSY

• Precision measurements of proton structure
  – HERA++ (esp. charged current measurements)
  – Neutron PDFs via deuteron w/ forward proton tagging

• High Parton Density
  – Evolution @ low x, non-linear evolution (saturation)

• Nuclear PDFs and SIDIS
  – Improved PDFs, $g^A(x, Q^2)$ via $F_L$ and $F_2^c$
  – Evolution & fragmentation of quark in nucleus
LHeC Nuclear Physics Program

QCD @ high parton density (unitarity limit), parton saturation in nucleons and nuclei

Measure the initial state leading to (strong coupled) quark gluon plasma

Precision nuclear and neutron parton distributions (especially gluons) over wide kinematic range

Study evolution of struck quark in nucleus over large range of $v, Q^2$
LHeC: Ring-Ring Option

Addition of electron ring in LHC tunnel (a la LEP)

Electrons from injection energy to ~ 80 GeV

Luminosity ~ $10^{33}$ cm$^2$/s

• Electron ring technologically straightforward.
  – But, significant logistical challenges.
    ⇒ e.g. compatibility with LHC operation
Ring-Ring Technical Developments

Placement of electron ring w/ services in LHC tunnel

Dipole magnet design (BNP)
O-shaped magnet with ferrite core

CMS Bypass (also ATLAS)
Linac-Ring Option(s)

\[ L = \frac{N_p \gamma}{4\pi \varepsilon_0 \beta^*} \cdot \frac{P}{E_e} = 5 \cdot 10^{32} \cdot \frac{P}{MW} \cdot \frac{E_e}{GeV} \text{ cm}^{-2} \text{s}^{-1} \]

Linac-Ring ep/eA

LINAC Challenges

ILC type cavities 15-25 MV/m
Intense e^+ source
Energy limited by cost
Luminosity boost with energy recovery
10-15km of tunnel but independent of LHC
Linac-Ring options (Sept. 2009)

### 3-km long greenfield SC linac

<table>
<thead>
<tr>
<th>“ILC-like” SC linac parameters</th>
<th>Anders Eide</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHeC-RL scenario</td>
<td>lumi</td>
</tr>
<tr>
<td>final energy [GeV]</td>
<td>60</td>
</tr>
<tr>
<td>cell length [m]</td>
<td>24</td>
</tr>
<tr>
<td>cavity fill factor</td>
<td>0.7</td>
</tr>
<tr>
<td>tot. linac length [m]</td>
<td>3000</td>
</tr>
<tr>
<td>cav. gradient [MV/m]</td>
<td>13</td>
</tr>
<tr>
<td>operation mode</td>
<td>CW (ERL)</td>
</tr>
</tbody>
</table>

RF frequency: ~700 MHz

- 4 passes
- 2 passes

---

*we can use the same linac for all energies!*

(different klystrons and modulators for cw and pulsed mode)

---

- Accelerator WG summary from Divonne LHeC meeting September 2009.

---

F. Zimmermann, CERN; Divonne 2009
LHeC Options - Luminosity

- Accelerator WG summary from Divonne LHeC meeting September 2009.
Interaction Region Design

- Progress on both ring-ring (top) and linac-ring (bottom) interaction region design
- Entire WG devoted to IR design
• Requirement: acceptance down to 1°
• Outer and forward muon detectors not shown
LHeC Detector: version for low x Physics

Muon chambers
(fwd,bwd,central)

Coil (r=3m l=8.5m, 2T)
[Return Fe not drawn,
2 coils w/o return Fe studied]

Central Detector

Hadronic Calo (Fe/LAr)
El.magn. Calo (Pb,Sc)
GOSSIP (fwd+central)
[Gas on Slimmed Si Pixels]
[0.6m radius for 0.05% * pt in 2T field]

Pixels
Elliptic beam pipe (~3cm)

Fwd Spectrometer
(down to 1°)

Tracker
Calice (W/Si)
FwdHadrCalo

Bwd Spectrometer
(down to 179°)

Tracker
Spacial (elm, hadr)

Extensions in fwd direction (tag p,n,d) and backwards (e,γ)
LHeC Detector (3)

• Very forward measurements essential:
  – calorimetry, roman pots, ...
  ⇒ Needs much more work

• New idea being studied: active magnets

Possible way to allow closer focusing magnets while retaining small angle acceptance
LHeC - Low $Q^2$ Kinematic Coverage

- Assuming coverage down to $1^\circ$, 50 GeV electron energy

- Acceptance down to $x \sim 10^{-6}$, $Q^2 \sim 1$ GeV$^2$
  - For both e-p, e-Pb.

\[ Q^2 (\text{GeV}^2) \]

- $p(7000) + e(50)$
- $p(920) + e(30)$

\[ Q^2_{\text{sat,GBW}} (~ \text{proton}) \]

\[ \theta_e = 179^\circ \]

\[ Q^2 (\text{GeV}^2) \]

- $^{208}\text{Pb}(2750) + e(50)$
- $Q^2_{\text{sat,GBW}} (^{208}\text{Pb})$

\[ \theta_e = 179^\circ \]

[Armesto]

Existing data
(approximate)
LHeC: $F_2$ and $F_L$ impact

- Talk by Albacete at Divonne 2009 Meeting

Extrapolating HERA models of $F_2$ (Albacete)

NNPDF NLO DGLAP uncertainties explode @ low $x$ and $Q^2$
Formally, wide range of possibilities allowed, still fitting HERA

$F_2(x, Q^2) \quad Q^2 = 2\, GeV^2$

$F_L(x, Q^2) \quad Q^2 = 2\, GeV^2$

- 'Modern' dipole models, containing saturation effects & low $x$ behaviour derived from QCD give a much narrower range
- c.f. 2% errors on LHeC $F_2$ pseudo-data, 8% on $F_L$ pseudo-data... we should be able to distinguish...
LHeC: $F_2$ and $F_L$ impact (2)

- Using measured $F_2$ and $F_L$ in e-p can significantly improve knowledge of gluon distribution

- And test predictions from the previous slide.

\[ F_2 \text{ only} \]

\[ F_2 \text{ and } F_L \]
e-A LHeC Impact on Nuclear PDFs

Extension of EPS09 analysis using LHeC e-Pb pseudo-data

Global NLO fit with LHeC pseudodata [from N. Armesto] included
[results from Hannu Paukkunen]

Lead, A=208

- From Divonne 2009 meeting, low-x summary
Diffractive Kinematics

Diffractive Kinematic Plane at LHeC

- Higher $E_e$ yields acceptance at higher $Q^2$ (pQCD), lower $x_{IP}$ (clean diffraction) and $\beta$ (low $x$ effects)
- Similar to inclusive case, $170^\circ$ acceptance kills most of plane
Project Status

• From talk by M. Klein at NuPECC scoping workshop, October 2009.

2007: (r)ECFA and CERN invite for CDR
2008: Reports to NuPECC (9/08), ICFA (10/08) and ECFA (11/08)
2009: 2nd workshop on the LHeC under auspices of CERN, ECFA, NuPECC

2010: Conceptual Design Report (CDR)
     [machine, interaction region, detector, physics: BSM, QCD+elweak, HPD]

Further consideration depends on CDR and LHC

Project may be realised within 10 years and thus fit to the 2nd phase of LHC

• CERN and ECFA are supporting development of LHeC CDR, due 2010.
  – Role in NuPECC long range plan under consideration
LHeC Physics Program (Reprise)

- From talk by M. Klein at NuPECC scoping workshop, October 2009.

Physics Programme of the LHeC

- Unfolding completely the partonic structure of the proton (neutron and photon) and search for sub-substructure down to scales ten times below HERA's limit.
- Sensitive 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 Tera scale physics, in particular for singly produced new states (LQ, RPV SUSY, excited fermions), complementary to the LHC pp program.

- Exploration of high density matter (low x physics beyond the expected unitarity limit for the growth of the gluon density).
- Unfolding the substructure and parton dynamics inside nuclei and study of quark-gluon plasma matter, by an extension of the kinematic range of lepton-nucleus scattering by 4 orders of magnitude.

- “Our” physics figures prominently in LHeC goals.
LHeC CDR Outline

Conceptual Design Report
Large Hadron Electron Collider (LHeC) at CERN
DRAFT - February 2009

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
   1. Acceptance and Kinematics
   2. A Series of Measurements
   3. Compatibility with the LHC
   4. Proton, Deuteron and Ion Beams

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

6. A Linac-Ring Collider Concept
   1. Electron and Positron Sources, Polariisation
   2. Linac
   3. Interaction Region
   4. Beam Dump
   5. Infrastructure and Cost

7. A Detector for the LHeC
   1. Dimensions and General Requirements
   2. Coil
   3. Calorimeters
   4. Tracking
   5. Options for the Inner Detector Region
   6. Detector Simulation and Performance

8. Summary
   1. Physics Highlights
   2. Parameters
   3. Concluding Remarks

Appendix
   1. Tasks for a TDR
   2. Building and Operating the LHeC
Possible LHeC Scenario

• Accelerator WG summary from Divonne LHeC meeting September 2009.

one staged schedule – $E$ first

- **2019**: SLHC phase II
- **2021**: 60 GeV, pulsed
  \[ L_{ep} \sim 3 \times 10^{32} \text{ m}^{-2}\text{s}^{-1} \]
- **2023**: 100 GeV, pulsed,
  \[ \sim 2.2 \times 10^{32} \text{ m}^{-2}\text{s}^{-1} \]
- **2025**: 140 GeV, pulses,
  \[ 1.5 \times 10^{32} \text{ m}^{-2}\text{s}^{-1} \]
- **2028**: 60 GeV, cw, ER $\eta \sim 90\%$
  \[ 3 \times 10^{33} \text{ m}^{-2}\text{s}^{-1} \]
- **2030**: 60 GeV, cw, ER $\eta \sim 98\%$
  \[ 1.5 \times 10^{34} \text{ m}^{-2}\text{s}^{-1} \]

Only 40% of the linac are needed for first stage!

*Total electric wall-plug power 100 MW*
LHeC will probe the physics of the “initial state” of heavy ion collisions down to $x < 10^{-5}$ with $Q^2 > \sim 1 \text{ GeV}^2$. 

**A+A initial conditions (RHIC & LHC)**

- Gluon emission from (saturated?) nuclei
- Quark gluon plasma
- “re-confinement”

**Detection**

The physics here influences the physics here and determines the conditions here and influences how we interpret data from here.
Can we see failure of linear evolution (including low-x resummation) with e-p data from LHeC?

- NNPDF fits to pseudo-data w/ saturation (here FS04)
- Compare extracted PDFs, deviations indicate failure of linear evolution

⇒ Need $F_L$ to see significant
LHeC Data and PDFs, non-linearities?

J. Rojo, from CERN HPD workshop

- Similar conclusions w/ more modern saturation
Nuclear pseudo-data for a given set of assumptions re: nuclear running

- Excellent statistics for $F_2$, not so good for $F_L$
- $F_L$ still as necessary with nuclei?
Diffraction at LHeC: new possibilities

- Studies with 1 degree acceptance,
- Diffractive-PDFs
- Factorization in much bigger range
- Diffractive masses $M_X \sim 100 \text{GeV}$ with $x_{IP} = 0.01$
- $X$ can include $W,Z,b$

Forshaw, Marquet, Newman

Simulated diffractive data available

From talk by P. Newman Divonne 2008
Exclusive Diffraction at LHeC

SPL Scenario - photoproduction cross secs

- J/ψ cross section at $Q^2 = 0.1\,\text{GeV}^2$
  - $E_p = 20\,\text{GeV}$, $E_y = 7\,\text{TeV}$, $\sqrt{s} = 748.331\,\text{GeV}$
  - Angular acceptance to 1 degrees
  - Luminosity of $2\,\text{fb}^{-1}$

- ϒ cross section at $Q^2 = 0.1\,\text{GeV}^2$
  - $E_p = 20\,\text{GeV}$, $E_y = 7\,\text{TeV}$, $\sqrt{s} = 748.331\,\text{GeV}$
  - Angular acceptance to 1 degrees
  - Luminosity of $2\,\text{fb}^{-1}$

LHeC Simulation
H1 (HERA-I)

Dedicated Low $x$ Ring-Ring Scenario

- J/ψ cross section at $Q^2 = 0.1\,\text{GeV}^2$
  - $E_p = 50\,\text{GeV}$, $E_y = 7\,\text{TeV}$, $\sqrt{s} = 1183.22\,\text{GeV}$
  - Angular acceptance to 1 degrees
  - Luminosity of $2\,\text{fb}^{-1}$

- ϒ cross section at $Q^2 = 0.1\,\text{GeV}^2$
  - $E_p = 50\,\text{GeV}$, $E_y = 7\,\text{TeV}$, $\sqrt{s} = 1183.22\,\text{GeV}$
  - Angular acceptance to 1 degrees
  - Luminosity of $2\,\text{fb}^{-1}$

LHeC Simulation
H1 (HERA-I)

Live, e/p only

CERN HPD workshop

pseudo-data for two different LHeC scenarios
Exclusive diffractive J/ψ production

J/ψ Decay Product Polar Angles

As Ee increases, leptons pushed further and further into outgoing electron beam direction (losing high W acceptance)
Exclusive diffractive $J/\psi$ production (2)

Acceptances for $J/\psi$ in Different Scenarios

- For a limited ($170^\circ$) backward, geometrical acceptance in $W$ does not improve beyond SPL scenario as $E_e$ increases!
- For $\theta < 179^\circ$, acceptance high at large $E_e$ to kinematic limit