An Overview of the LHeC

Paul Laycock
Tools to unfold nuclear structure

- Historically, we build tools which attack the luminosity and energy frontier
- Ideally we want the best tools possible
Unfolding nuclear structure

Rutherford  SLAC  HERA

Time
An incomplete history of deep-inelastic scattering

- A rich history of exploiting scattering experiments to study structure, culminating in the HERA electron-proton machine
- Confirmation of the QCD picture of the proton, structure mapped with high precision...
An incomplete history of deep-inelastic scattering

- A rich history of exploiting scattering experiments to study structure, culminating in the HERA electron-proton machine
- Confirmation of the QCD picture of the proton, structure mapped with high precision...
An incomplete history of deep-inelastic scattering

- A rich history of exploiting scattering experiments to study structure, culminating in the HERA electron-proton machine
- Confirmation of the QCD picture of the proton, structure mapped with high precision...
- But QCD is a very subtle theory and not easily mastered, it has not given up all of its secrets
What HERA didn’t or couldn’t do

• There was no electron-ion program at HERA
  • Nuclear parton densities are largely unknown
  • No deuterons - no test of isospin symmetry comparing protons with neutrons
  • How does nuclear matter affect partons and their dynamics?
  • Saturation
• The kinematic reach and luminosity were too low
  • Saturation
  • The proton parton densities can not be fully unfolded without making assumptions
  • Charm and beauty are poorly know, strange is unknown
  • The gluon is poorly known at low and high x
  • There is no precision measurement of $\alpha_s$
  • No instantons or odderon? Why not?
• To make progress, we need a successor to HERA that includes ions
• Thankfully half of that machine has already been built in Geneva
The LHeC Concept

The LHeC $ep$ program would run simultaneously with the LHC $pp$ and $HI$ programs (small $ep$ tuneshifts)

- Collide a new polarised electron beam $E \sim 60$ GeV with a proton/HI beam of the LHC
The LHeC - Ring-Ring

To develop the concept, an IP is needed and Alice has been used.

- Power Limit of 100 MW wall plug
- “ultimate” LHC proton beam
- 60 GeV $e^\pm$ beam

\[ L = 2 \times 10^{33} \text{cm}^{-2}\text{s}^{-1} \Rightarrow O(100) \text{fb}^{-1} \]

HERA 1.5 $10^{31} \Rightarrow 1 \text{fb}^{-1} (H1+ZEUS)$

- Either by installing a new electron storage ring in the LHC tunnel (Pol~40%)
The LHeC - Linac-Ring

To develop the concept, an IP is needed and Alice has been used.

- Or by building a new super-conducting RF electron linac (Pol~90%)

Pulsed, 60 GeV: $\sim 10^{32} \text{cm}^{-2}\text{s}^{-1}$
High luminosity:
Energy recovery: $P = P_0/(1-\eta)$
$\beta^* = 0.1\text{m}$
[5 times smaller than LHC by reduced $I^*$, only one p squeezed and IR quads as for HL-LHC]
$L = 10^{33} \text{cm}^{-2}\text{s}^{-1} \rightarrow O(100) \text{fb}^{-1}$
LHeC development

2007: Invitation by SPC to ECFA and by (r)ECFA to work out a design concept

2008: First CERN-ECFA Workshop in Divonne (1.-3.9.08)

2009: 2nd CERN-ECFA-NuPECC Workshop at Divonne (1.-3.9.09)

2010: Report to CERN SPC (June)
      3rd CERN-ECFA-NuPECC Workshop at Chavannes-de-Bogis (12.-13.11.10)
      NuPECC: LHeC on Longe Range Plan for Nuclear Physics (12/10)

2011: Draft CDR (530 pages on Physics, Detector and Accelerator) (5.8.11)
      refereed and being updated

2012: Discussion of LHeC at LHC Machine Workshop (Chamonix)
      Publication of CDR + 2 Contributions to European Strategy [arXiv]
      Chavannes workshop (June14-15, 2012) – CERN: Linac+TDR Mandate
      ECFA final endorsement of CDR
• 600 page report published on the conceptual design, 200 authors from 60 institutes
• Refereed by 23 world-leading experts invited by CERN
LHeC mandate from CERN

The mandate for the technology development includes studies and prototyping of the following key technical components:

- Superconducting RF system for CW operation in an Energy Recovery Linac, (high Q0 for efficient energy recovery). The studies require design and prototyping of the cavity, couplers and cryostat.
- Superconducting magnet development of the insertion regions of the LHeC with three beams. The studies require the design and construction of short magnet models.
- Studies related to the experimental beam pipes with large beam acceptance in a high synchrotron radiation environment.
- The design and specification of an ERL test facility for the LHeC.
- The finalization of the ERL design for the LHeC including a finalization of the optics design, beam dynamic studies and identification of potential performance limitations.

The above technological developments require close collaboration between the relevant technical groups at CERN and external collaborators.

Given the rather tight personnel resource conditions at CERN the above studies should exploit where possible synergies within existing CERN studies (e.g. SPL and ESS SC RF, HL-LHC triplet magnet development and collaboration with ERL test facility outside CERN).

- CDR summarised at a final workshop in June 2012 after the CDR publication
- Above taken from slides of S. Bertolucci as he concluded the workshop
- Choose the linac-ring - CERN will build an ERL test facility
The LHeC

- Build a new super-conducting RF electron linac (Pol~90%)

Pulsed, 60 GeV: $\sim10^{32}\text{cm}^{-2}\text{s}^{-1}$

High luminosity:
Energy recovery: $P = P_0/(1-\eta)$

$\beta^* = 0.1\text{m}$

[5 times smaller than LHC by reduced $I^*$, only one $p$ squeezed and IR quads as for HL-LHC]

$L = 10^{33}\text{ cm}^{-2}\text{s}^{-1} \to O(100)\text{ fb}^{-1}$
Accelerator Design: Participating Institutes
60 GeV Energy Recovery Linac

Two 10 GeV energy recovery Linacs, 3 returns, 720 MHz cavities
LHeC machine parameters

<table>
<thead>
<tr>
<th>parameter [unit]</th>
<th>LHeC</th>
</tr>
</thead>
<tbody>
<tr>
<td>species</td>
<td>e, p, $^{208}\text{Pb}^{82+}$</td>
</tr>
<tr>
<td>beam energy (/nucleon) [GeV]</td>
<td>60, 7000, 2760</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25, 100</td>
</tr>
<tr>
<td>bunch intensity (nucleon) [$10^{10}$]</td>
<td>0.1 (0.2), 0.4, 17 (22), 2.5</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>6.4 (12.8), 860 (1110), 6</td>
</tr>
<tr>
<td>rms bunch length [mm]</td>
<td>0.6, 75.5</td>
</tr>
<tr>
<td>polarisation [%]</td>
<td>90 (e$^+$ none), none, none</td>
</tr>
<tr>
<td>normalised rms emittance [$\mu$m]</td>
<td>50, 3.75 (2.0), 1.5</td>
</tr>
<tr>
<td>geometric rms emittance [nm]</td>
<td>0.43, 0.50 (0.31)</td>
</tr>
<tr>
<td>IP beta function $\beta_{x,y}^*$ [m]</td>
<td>0.12 (0.032), 0.1 (0.05)</td>
</tr>
<tr>
<td>IP spot size [$\mu$m]</td>
<td>7.2 (3.7), 7.2 (3.7)</td>
</tr>
<tr>
<td>synchrotron tune $Q_s$</td>
<td>0.0001 (0.0002)</td>
</tr>
<tr>
<td>hadron beam-beam parameter</td>
<td>6 (30)</td>
</tr>
<tr>
<td>lepton disruption parameter D</td>
<td>0 (detector-integrated dipole)</td>
</tr>
<tr>
<td>crossing angle</td>
<td>0.91 (0.67)</td>
</tr>
<tr>
<td>hourglass reduction factor $H_{hg}$</td>
<td>1.35 (0.3 for e$^+$)</td>
</tr>
<tr>
<td>pinch enhancement factor $H_D$</td>
<td>1.3, 0.81</td>
</tr>
<tr>
<td>CM energy [TeV]</td>
<td>1 (10), 0.2</td>
</tr>
<tr>
<td>luminosity / nucleon [$10^{33}$ cm$^{-2}$s$^{-1}$]</td>
<td></td>
</tr>
</tbody>
</table>

- ep luminosities of $10^{33}$ shown in the CDR, up to $10^{34}$ possible in an update sent to the European Strategy debate
- eA luminosities of $10^{32}$ for lead, $10^{31}$ for eD
- See talk of Vladimir Litvinenko
The Linac Ring design in situ @LHC

60 GeV Electron Accelerator

Two 1km long LINACs connected at CERN territory
Arcs of 1km radius: ~9km tunnel
3 passages with energy recovery

John Osborne (June LHeC Workshop)
RF Development

Frequency choice: \( n \times 120.237 \text{ MHz} \)
N=6: 721 MHz, n=11: 1.3GHz (XFEL)

- Detailed comparison (threshold current, cryo power, Rf power, size, cost, collaboration, synergy..)
- ALICE 1.3 GHz, not CW – only EU ERL facility operational
- Daresbury develops cryomodule for ESS (700 MHz)
- CERN: in house collaboration with SPL, and eRHIC/BNL

Accelerator physics motivation:
- ERL demonstration, FEL, \( \gamma \)-ray source, e-cooling demo!
- Ultra-short electron bunches
- One of the 1\textsuperscript{st} low-frequency, multi-pass SC-ERL
- synergy with SPL/ESS and BNL activities
- High energies (200 ... 400 MeV) & CW
- Multi-cavity cryomodule layout – validation and gymnastics
- Two-Linac layout (similar to LHeC)
- MW class power coupler tests in non-ER mode
- Complete HOM characterization and instability studies!
- Cryogenics & instrumentation test bed ... E.Jensen

Steps: Design of LHeC ERL TF, cavity-cryo module (hi Q), lattice, optics, magnets, source, ....
Watch out for surprises as humming bird:
Building international collaboration
(CERN,Daresbury, Jlab, others?)

beam structure at ALICE with 230-kV DC gun voltage
Tentative study of multipass optics and lattice

Development of LHeC Testfacility at CERN in international collaboration

(Jlab, BNL, Mainz, AsTEC...)

Alex Bogacz, JLab, August 21, 2012
Magnets Developments

Prototypes for Ring dipoles
Fabricated and tested by CERN (top) and Novosibirsk

1/2m dipole model
Full scale prototype
Quadrupole for Linac

LR recirculator dipoles and quadrupoles
New requirements (aperture, field)?
Combined apertures?
Combined functions (for example, dipole + quad)?
LR linac quadrupoles and correctors
New requirements (aperture, field)?
More compact magnets, maybe with at least two families for quadrupoles?
Permanent magnets / superconducting for quads?
A. Milanese, Chavannes workshop

Magnets for ERL test stand

Collaboration of CERN, Daresbury and Budker (Novosibirsk)
Interaction Region Developments

Have optics compatible with LHC and $\beta^*=0.1m$
Head-on collisions mandatory $\rightarrow$
High synchrotron radiation load, dipole in detector

**Specification of Q1 – NbTi prototype (with KEK?)**
Revisit SR (direct and backscattered),
Masks+collimators
Beam-beam dynamics and 3 beam operation studies

Optimisation: HL-LHC uses IR2 quads to squeeze IR1
(“ATS” achromatic telescopic squeeze) Start in IR3. $\rightarrow$ R.Tomas et al.

Beam pipe: in CDR 6m, Be, ANSYS calculations
Composite material R+D, prototype, support..
$\rightarrow$ Essential for tracking, acceptance and Higgs
High-gradient SC IR quadrupoles based on Nb$_3$Sn for colliding proton beam with common low-field.

As shown by F. Zimmermann at Chamonix12.
The LHeC Detector (see talk of Alessandro Polini)

- High precision, state of the art detector, low noise
- Efficient flavour tagging down to $1^\circ$
- No R&D
- Modular for fast installation and upgrade
- Affordable

So what could we do with this?
The optics of the LHeC means no pile-up, a clean unfolding of the proton structure with 100 times the HERA luminosity over a huge kinematic range.

Thanks to the large acceptance, precision data at even the lowest and highest $x$. 
How strange is the proton?

- The LHeC would measure the strangeness of the proton with very high precision
- Positrons and electrons would disentangle strange from anti-strange

Charm tagging employing the high acceptance silicon tracker
How charming is the proton?

The LHeC would measure the charm content of the proton with high precision across more than 5 decades in $x$ and $Q^2$.

These data could determine the charm mass to ~3 MeV.

It will finally measure the charm content at high $x$ - is there intrinsic charm?

Charm tagging employing the high acceptance silicon tracker
How beautiful is the proton?

Beauty tagging employing the high acceptance silicon tracker

- Thanks to the vastly superior tracking detector, the beauty of the proton will be fully appreciated, finally measuring this precisely across the complete kinematic range.
- Of high importance for very many searches at the LHC.
The new era in proton PDFs

- The LHeC completely unfolds the gluon field in the proton
- Not to mention the expected improvements from adding deuteron data
  - Test whether the neutron d is equivalent to the proton u
  - Have another handle on singlet / non-singlet evolution
- Assumptions will be replaced by data, leading to a new era in proton PDFs
- See talk by Voica Radescu
- Especially important at high x for new particle searches, and at low x...
What happens at low $x$?

- The rise of the gluon can’t continue forever
- Recombination $(gg \rightarrow g)$ / saturation
- LHeC has the correct kinematic configuration to access low $x$ to study this process with a hard probe
- Understand saturation in perturbative QCD
Low x and diffraction

- Inclusive and exclusive diffraction will be studied at LHeC over a hugely expanded kinematic range, also using dedicated detectors
- See talk of Pierre Van Mechelen
- Of particular interest - the sensitivity of exclusive vector meson production to saturation
Paint it black

- Two ways to make the target blacker at LHeC:
  - go to low x in ep
  - increase A
Kinematic coverage of ep and eA

- The understanding of nuclear PDFs would undergo a revolution given the ~4 orders of magnitude increase in kinematic range.
- Pin down the initial conditions of nuclei to better understand pA and AA.
- Thanks to the LHeC detector, measure charm and beauty in nPDFs for the first time.
In-medium Hadronisation

The study of particle production in eA (fragmentation functions and hadrochemistry) allows the study of the space-time picture of hadronisation (the final phase of QGP).

Low energy ($\nu$): need of hadronization inside.
Parton propagation: pt broadening
Hadron formation: attenuation

High energy ($\nu$): partonic evolution altered in the nuclear medium.

LHeC:
+ study the transition from small to high energies in much extended range wrt. fixed target data
+ testing the energy loss mechanism crucial for understanding of the medium produced in HIC
+ detailed study of heavy quark hadronisation ...

W. Brooks, Divonne09
LHeC and heavy ion physics

- The key experimental advantage with LHeC - the kinematics of the struck parton are known with high precision
- Precision measurements for a precise understanding
- See talk of Anna Stasto
eA vs ep

- File under “things I don’t understand very well about QCD”
- More from Anna
Precision $\alpha_s$ measurement - Grand Unification?

- It may be that the forces unify, i.e. have the same strength, at high energy
- Verifying that demands improvements in our knowledge of $\alpha_s$ which is by far the least well known of the fundamental couplings
- Presently known to ~1% precision, it would be determined at the per mille level..
- ..and at a couple per mille for $Q^2 > 20$ GeV$^2$, i.e. no non-perturbative effects
- Higgs cleanly produced in CC reactions, ~hundred reconstructed events
- Studied with the Higgs decaying to bb, possible with LHeC tracking detector
- Signal significance of ~16 found, clearly worthy of further study!
- See talk of Voica for more details
Many of the channels at LHC will be limited by PDF uncertainties

With the LHeC, the huge improvements in knowledge of PDFs, precision of $\alpha_s$ will remove this, allowing the full exploitation of the LHC data for Higgs physics
time line of CERN HEP projects


LEP  Constr.  Physics  Upgr.


HL-LHC  Design, R&D  Constr.  Physics

LHeC  Design, R&D  Constr.  Physics

HE-LHC  Design, R&D  Constr.  Physics

runs in parallel to HL-LHC; tight R&D schedule

follows HL-LHC; R&D & protot. time < for LHC
Summary

LHeC represents a fantastic opportunity to understand nuclear structure and QCD with high precision
Support material


Web page with much more information: cern.ch/lhec
Backup
Precision electroweak measurements

\[ \sin^2 \theta_W \]

At LHeC, measured using the polarisation asymmetry

- An interesting proposal to measure the electroweak mixing angle using polarisation asymmetry measurements
- Good precision and the scale dependence measured in one experiment
- To be pursued further

The vector and axial-vector weak NC couplings to the u and d quarks would be measured to very high precision (look closely!)
Current knowledge of the valence quarks

- The valence structure of the proton may be known, the details are not
- The range of answers offered by the latest and greatest is surprisingly varied
The proton has its ups and downs

- The LHeC would be able to constrain the valence quarks across the whole kinematic range to better than \(~2\%) precision

- c.f. LHC searches continue to push towards higher masses, i.e. higher x
How strange is the proton?

- Very strange? The spread of distributions looks appropriately strange
- But not really strange, the current constraints from data are very poor and consequently the strange content of the proton is very poorly known
How to treat heavy flavours?

- We expect to see many top quarks (100,000 events) at the LHeC, opening up the field of top PDFs

- Need to have 6 flavour-number scheme (see talk of Pascaud)

- The LHeC would map the transition between the massive and massless approaches, precision heavy flavour data invaluable for theory
Measuring fundamentals

\[ \sin^2 \theta_W \]

At LHeC, measured using the polarisation asymmetry

\[ \alpha_s \] scenarios

<table>
<thead>
<tr>
<th>case</th>
<th>cut ([Q^2 \text{ in GeV}^2])</th>
<th>relative precision in (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERA only (14p)</td>
<td>(Q^2 &gt; 3.5)</td>
<td>1.94</td>
</tr>
<tr>
<td>HERA+jets (14p)</td>
<td>(Q^2 &gt; 3.5)</td>
<td>0.82</td>
</tr>
<tr>
<td>LHeC only (14p)</td>
<td>(Q^2 &gt; 3.5)</td>
<td>0.15</td>
</tr>
<tr>
<td>LHeC only (10p)</td>
<td>(Q^2 &gt; 3.5)</td>
<td>0.17</td>
</tr>
<tr>
<td>LHeC only (14p)</td>
<td>(Q^2 &gt; 20)</td>
<td>0.25</td>
</tr>
<tr>
<td>LHeC+HERA (10p)</td>
<td>(Q^2 &gt; 3.5)</td>
<td>0.11</td>
</tr>
<tr>
<td>LHeC+HERA (10p)</td>
<td>(Q^2 &gt; 7.0)</td>
<td>0.20</td>
</tr>
<tr>
<td>LHeC+HERA (10p)</td>
<td>(Q^2 &gt; 10)</td>
<td>0.26</td>
</tr>
</tbody>
</table>

- The LHeC would be able to measure the value of \(\sin^2 \theta_W\) at different \(\mu(Q^2)\)
- The strong coupling constant, presently known to \(\sim 1\%\) precision, would be determined at the per mille level
- At a couple per mille for \(Q^2 > 20\ \text{GeV}^2\), i.e. no non-perturbative effects
Neutral Current Boson Interference

- Limited measurements of the interference terms contributing to proton structure
- LHeC measures $F_2^{YZ}$ for the first time - probing parity violation at small distances
- Also measures $xF_3^{YZ}$ with good precision - probing the valence at $x < 10^{-3}$
What lies beyond?

- Is nature supersymmetric?

- Normally consider pair-production of SUSY particles at the LHC which decay into the lightest SUSY particle, they can’t decay if R-parity is conserved

  - Striking missing energy signatures in the detector as the LSP escapes

- But if R-parity isn’t conserved?

- More on SUSY and LHeC in Monica’s talk tomorrow
What lies beyond?

- Why are there quarks and leptons?
- They both experience the electromagnetic and weak forces, but only quarks feel the strong force, why??
- Perhaps quarks and leptons are composites of more fundamental particles, many theories, predict leptoquarks (may also be squarks in RPV SUSY)
- The LHeC provides lepton and baryon number in the initial state, a good leptoquark factory if such things exist
Clean signatures of new physics - leptoquarks
Leptoquarks

- Similar or better sensitivity than LHC
- The key difference is that, if they exist, the LHeC can characterise them, measuring their quantum numbers
- Similar story for other new physics, e.g. excited electrons (see talk by Azuelos)