Design Considerations

Two options:
- Ring-Ring collider
- Linac-R\textsuperscript{2} Ring collider with Energy Recovery

IR Layout

Planning Timeline

Next steps

On behalf of the LHeC Collaboration!
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 and thus fundamental and deserves to be further worked out 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 therefore proposed to hold two workshops (2008 and 2009), under the auspices of rECFA and ECFA, 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.

LHeC Proposal endorsed by ECFA (30.11.2007)

Unanimously supported by rECFA and ECFA plenary in November 2007
### NuPECC – Roadmap 5/2010: New Large-Scale Facilities

<table>
<thead>
<tr>
<th>Project</th>
<th>R&amp;D</th>
<th>Construction</th>
<th>Commissioning</th>
<th>Exploitation</th>
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<td>R&amp;D</td>
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<td>Design Study</td>
<td>R&amp;D</td>
<td>Engineering Study</td>
<td>Construction/Commissioning</td>
</tr>
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</table>

We are here: at the start of R&D
Design Considerations

LHC hadron beams: $E_p = 7$ TeV; CM collision energy: $E^2_{CM} = 4 E_p^2 = 6300$ GeV

Integrated $e^\pm p : O(100) \text{ fb}^{-1} \approx 100 \times L(\text{HERA}) \rightarrow$ synchronous

Luminosity $O\left(10^{33}\right) \text{ cm}^{-2}\text{s}^{-1}$ with 100 MW power consumption $\rightarrow$ Beam Power $< 70 \text{ MW}$

Start of LHeC operation together with HL-LHC in 2023 (installation in LS3 in 2022)

e Ring in the LHC tunnel (Ring-Ring)

Luminosity \- Energy & Power tradeoff

We chose 60GeV Beam Energy as reference case for comparison in the CDR

LHeC Mini Workshop, 18th April 2013

Oliver Brüning, CERN
LHeC options: RR and LR

RR LHeC: new ring in LHC tunnel, with bypasses around existing experiments

LR LHeC: recirculating linac with energy recovery, or straight linac

e-/e+ injector 10 GeV, 10 min. filling time
1. Design for synchronous ep and pp operation (including eA) \(\rightarrow\) after LS3 which is about 2025 – no firm schedule exists for HL-LHC, but it may operate until ~2035

2. LHeC is a new collider: the cleanest microscope of the world, a complementary Higgs facility, a unique QCD machine with a striking discovery potential, with possible applications as \(\gamma\gamma \rightarrow H\) or injector to TLEPP or others AND an exciting new accelerator project

3. CERN Mandate to develop key technologies for the LHeC for project decision after start of LHC Run II and in time for start parallel to HL LHC phase
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 $Q_0$ for efficient energy recovery)
- 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 dynamics 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 with existing CERN studies.
LHeC: Ring-Ring Option

Challenge 1: Bypassing the main LHC detectors

Without using the survey gallery the ATLAS bypass would need to be 100m away from the IP or on the inside of the tunnel!

For the CDR the bypass concepts were decided to be confined to ATLAS and CMS

ca. 1.3 km long bypass
ca. 170m long dispersion free area for RF
Challenge 3: Installation with LHC circumference:

- Requires support structure with efficient montage and compact magnets.
LHeC: Ring-Ring Option

Challenge 2: Integration in the LHC tunnel

No principal problem found yet!
(Still missing 3D integration study)

Cryo link in IR3
LHeC Ring-Ring dipole 400 mm long CERN model

- interleaved ferromagnetic laminations
- air cooled
- two turns only, bolted bars
- 0.4 m models with different types of iron

Magnet Parameters of the full length magnet

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<th>Beam Energy [GeV]</th>
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<td>Number of magnets</td>
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<td>Power per magnet [W]</td>
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<td>Weight [tons]</td>
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</table>

Prototype of light magnet design shows that required field quality and reproducibility is feasible!
R-R installation is very challenging! LHeC activities essentially only inside LHC tunnel! leaves LS1 and LS2 too soon to be used for LHeC installation! current 10-year plan for LHC operation within shutdown for LHeC.
LHeC: Linac-Ring Option Considered
Various Layout Options

- **p-60**
  - 0.34 km injector
  - 1.67 km linac
  - Luminosity limited by power

- **p-140’**
  - Injectors
  - 3.9 km linac
  - 70 GeV
  - High energy
  - Luminosity limited by power and Cost!

- **1.0 km**
  - LHC
  - IP

- **2.0 km**
  - 10 GeV linac
  - 70 GeV linac

- **3.9 km**
  - 70 GeV linac
  - IP

- **High luminosity**
  - Baseline

"Least expensive"

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Oliver Brüning, CERN
**LHeC: Baseline Linac-Ring Option**

**Challenge 1:** Super Conducting Linac with Energy Recovery & high current (> 6mA)

Two 1 km long SC linacs in CW operation

- Installation fully decoupled from LHC operation!
- Requires cryogenic system comparable to LHC system!

**Challenge 2:** Relatively large return arcs

- Ca. 9 km underground tunnel installation
- Total of 19 km bending arcs
- Same magnet design as for RR option: > 4500 magnets
LINAC – Ring: connection to the LHC

LHeC CDR based on 721 MHz cavity design

But RF Frequency has been re-optimized after publication of the CDR!

800 MHz chosen after CDR

- 600 - 4m long dipoles per arc
- 240 - 1.2m long quadrupoles per arc

- 15 LHeC Mini Workshop, 18th April 2013

Oliver Brüning, CERN
Interaction Region: Accommodating 3 Beams

Small crossing angle of about 1 mrad to avoid (Dipole in detector? Crab cavities? Design) Synchrotron radiation – direct and back, absorption … recall HERA upgrade …

Focus of current activity

First conceptual SC magnet designs exist

But still requires additional design work and R&D!

Synergies with HL-LHC triplet development!

1\textsuperscript{st} quad (sloping deflect) MQY cables, 4600 A

2\textsuperscript{nd} quad: 3 beams in horizontal plane separation 8.5 cm, MQY cables, 7600 A
LHeC Planning and Timeline

We assume the LHC will reach end of its lifetime with the end of the HL-LHC project:

- Goal of integrated luminosity of 3000 fb\(^{-1}\) with 200 fb\(^{-1}\) to 300 fb\(^{-1}\) production per year ➔ ca. 10 years of HL-LHC operation
- Current planning based on HL-LHC start in 2022 ➔ end of LHC lifetime by 2032 to 2035

LHeC operation:

- Luminosity goal based on ca. 10 year exploitation time (➔ 100 fb\(^{-1}\))
- LHeC operation beyond or after HL-LHC operation will imply significant operational cost overhead for LHC consolidation
Ring-Ring option:

- We know we can do it: → LEP 1.5
- Challenge 1: integration in tunnel and co-existence with LHC HW
- Challenge 2: installation within LHC shutdown schedule

Linac-Ring option:

- Installation decoupled from LHC operation and shutdown planning
- Infrastructure investment with potential exploitation beyond LHeC
- Challenge 1: technology → high current, high energy SC ERL
- Challenge 2: Positron source
LHeC CDR:

Details remain to be addressed

• Decision to focus R&D work on LR technologies over coming 4 years

➡ Main Conclusion so far:

LHeC can be realized in parallel with HL-LHC if necessary studies are not delayed!
Beam Pulses:
- Parameter list does not consider gaps in LHC beam
  - Fewer bunches with more charge
- Fast beam-ion instability may require a long gap
  - All ions are trapped in continuous beam ($f_c < f_{\text{limit}}$)
  - Beam will become unstable before neutralisation is reached
- Fix LHeC circumference to be $1/n$ of LHC
  - Each LHC bunch always or never collides with electron bunches
- Increase bunch charge by 50% to $3 \times 10^9$
  - Needs to be reviewed
Beam Instabilities:

Increased bunch charge
To allow for ion-clearing gaps
$N=3\times10^9$

Note: bunches were placed in the gaps

$F_{\text{rms}}=1.05$ for ILC cavity
$F_{\text{rms}}=1.001$ for SPL cavity

Beam is stable for both cases but more margins for lower RF frequency

Optimum choice for LHeC RF frequency?
Beam-Beam effects:

N = 3 \times 10^9

Beam-beam effect included as linear kick

Result depends on seed for frequency spread

“worst” of ten seed shown

F_{rms} = 1.135 for ILC cavity

F_{rms} = 1.002 for SPL cavity

Beam is stable but very small margin with 1.3GHz cavity

⇒ Optimum choice for LHeC RF frequency?
Review of the SC RF frequency:

- HL-LHC bunch spacing requires bunch spacing with multiples of 25ns (40.079 MHz)

Frequency choice: \( h \times n \times 40.079 \text{ MHz} \)

Symmetry in ERL: \( n=3 \Rightarrow h \times 120.237 \text{ MHz} \)

\( h=6: 721 \text{ MHz} \) or \( h=11: 1.323 \text{ GHz} \)

SPL & ESS: 704.42 MHz; ILC & XFEL: 1.3 GHz

 Frequencies are quite different (20MHz) from existing technologies! But having the harmonic number be a multiple of the ERL symmetry is not a strong requirement \( \Rightarrow \) asymmetric bunch patterns
Optimum RF Frequency: Power Considerations

Results from F. Marhauser

Erk Jensen at Daresbury meeting 12 March 2013

**Small-grain (normal) Nb:**
- Optimum frequency at 2K between 700 MHz and 1050 MHz
- Lower T shift optimum f upwards

**Large-grain Nb:**
- Optimum frequency at 2K between 300 MHz and 800 MHz
- Lower T shift optimum f upwards

**Graphs:**
- Plot of $P_{RF}/(L*E_{acc}^2)$ (W/(m*MV/m²)) vs. frequency (GHz) with $R_{res}$ (nΩ) as the y-axis.
- Two sets of curves for $\beta = 0.6$, $\beta = 0.8$, and $\beta = 1$.
- Points indicating optimum frequencies at $T = 2K$ and $T = 1.6K$.
Optimum RF Frequency: around 800 MHz

- \( F_{RF} = 20 \times 40.079 \text{ MHz} \rightarrow 801.58 \text{ MHz} \)

- Buckets with slightly unevenly spaced bunches

- One could vary the number of passes through the ERL:

- Synergy with HL-LHC: Higher Harmonic RF System and TLEP!
Have optics compatible with LHC ATS optics and $\beta^*=0.1\text{m}$
Head-on collisions mandatory $\Rightarrow$
High synchrotron radiation load, dipole in detector

Adapt LHeC to LHC ATS optics
Specification of Q1 – NbTi prototype

Revisit SR (direct and backscattered),
Masks+collimators
Beam-beam dynamics and 3 beam operation studies

Beam pipe: in CDR 6m, Be, ANSYS calculations
Composite material R+D, prototype, support..
$\Rightarrow$ Essential for tracking, acceptance and Higgs

Next Steps: Interaction Region Design

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Oliver Brüning, CERN
LHeC Planning and Timeline

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LHeC operation:

- Luminosity goal based on ca. 10 year exploitation time (100fb\(^{-1}\))
- LHeC operation beyond or after HL-LHC operation will imply significant operational cost overhead for LHC consolidation
LHeC Project is still on track for startup with HL-LHC:

- 10 years for the LHeC from CDR to project start.

(Other smaller projects like ESS and PSI XFEL plan for 8 to 9 years [TDR to project start] and the EU XFEL plans for 5 years from construction to operation start)

HERA required ca.10 years from proposal to completion

On schedule for launching SC RF development

⇒ Synergies with HL-LHC and TLEP

(LEP, LHC and LINAC4 at CERN and the European XFEL at DESY and the PSI XFEL). In
### New rough draft 10 year plan

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<td>2015</td>
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<tr>
<td>2016</td>
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**LHC**
- **LS1**: Machine: Splice Consolidation & Collimation in IR3
  - ALICE - detector completion
  - ATLAS - Consolidation and new forward beam pipes
  - CMS - FWD muons upgrade + Consolidation & Infrastructure
  - LHCb - consolidations
  - ?Cryo-collimation point

**Injectors**
- SPS upgrade
- ?SPS - LINAC4 connection & ?PSB energy upgrade

---

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</tr>
<tr>
<td>2022</td>
<td></td>
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</table>

**LHC**
- **LS2**: Machine: Collimation & prepare for crab cavities & RF cryo system
  - ATLAS: new pixel detector - detect. for ultimate luminosity.
  - ALICE - Inner vertex system
  - CMS - New Pixel. New HCAL Photodetectors. Completion of FWD muons upgrade
  - LHCb - full trigger upgrade, new vertex detector etc.

**Injectors**

---

**2022**
- **LS3**: Installation of the HL-LHC hardware
- **2023**
- **2024**
- **2025**
- **2026**
- **2027**
- **2028**
- **2029**
- **2030**

---

**LHeC Mini Workshop, 18th April 2013**

Oliver Brüning, CERN
LHeC: Post CDR Plans

Launching SC RF and ERL R&D and Establish collaborations:

- SC RF R&D has direct impact on cryo power consumption
  - Synergy with HL-LHC and TLEP!
- ERL is a hot topic with many applications
  - Synergy with national research plans: e.g. MESA

Magnet R&D activities:

- Normal conducting compact magnet design ✔
- Superconducting IR magnet design
  - Detailed magnet design depends on IR layout and optics
  - Optics & IR magnet design influence experimental vacuum beam pipe
Develop an ERL test facility @ CERN:

- Beam Dynamics for ERL operation → develop expertise at CERN
- Synergy with other research plans: SC RF and TLEP
Next Steps: RF Prototype and Test Facility

- Develop 2 RF Cryomodule Prototypes over the next 3 years
  - LHeC RF frequency choice driven by power considerations
    - Choice of ERL RF frequency: 801.58 MHz
    - Synergy with HL-LHC and Higher Harmonic RF system!

- Design an ERL test facility @ CERN:
  - Optimize magnet design for ERL return arcs

- Optimize and Iterate on LHeC ERL layout:
  - Optimization of linac configuration & of number of passages
  - Optimization of Civil Engineering layout
  - Optimization of Interaction Region ($L^*$) and Synchrotron Light
Reserve Transparencies
First conceptual cross-section

<table>
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<td>air</td>
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LHeC Mini Workshop, 18th April 2013

Attilio Milanese
Next Steps: LHeC IR Quadrupole

Luca Bottura @ Chamonix 2012

- Half-quad with field-free region, assembled using MQXC coils
  - 2.5 FTE
  - 500 kCHF
  - approx. 2 years till test

Large forces on the magnetic wedge (> 50 tons/m)
IR magnets

- **Ring-ring**
  - $G=140 \text{ T/m}$
  - $A=70 \text{ mm}$
  - $B_{\text{fringe}} = 30 \text{ mT}$
  - $O(15) \text{ kW SR power in the proton aperture}$

- **Linac-Ring**
  - $G=250-300 \text{ T/m}$
  - $A=90 \text{ mm}$
  - $B_{\text{fringe}} = 500 \text{ mT}$
  - $O(2) \text{ kW SR power in the proton aperture}$

By courtesy of S. Russenschuck

By courtesy of S. Russenschuck
Next Steps: ERL Layout Finalization

\[ \Delta \varepsilon \approx \langle H \rangle \frac{\gamma^5}{\rho^2} \]

\[ \rho \rightarrow 1 \rightarrow 0.85 \]

\[ \Delta \varepsilon \rightarrow 1 \rightarrow 1.38 \]
Next Steps: Test Facility and Magnets

Intend to build Collaboration of CERN Magnet Group for the dipole and possibly further arc magnets for the Test Facility (two turns) and the LHeC.

Initial designs for Linac magnets in CDR and further discussions/thoughts from Daresbury, CERN and BINP colleagues.
MESA

Mainzer Energieeffiziente Supraleitende Anlage
Mainz Energy recovering Superconducting Accelerator

S.C. 'BESSY' Module, \( \Delta E = 40 \text{MeV} \) (20MV/m, high cw gradient)

Conventional Injector
5MeV

Beam dump
5MeV

3.5m

2 Recirculations: Length = N*\( \lambda \)

Last recirc : Length = (M+1/2)\( \lambda \)

Exp

Parameters: (red beam for experiments)
\( E_{\text{max}} = 5-125 \ \text{MeV} \); \( I_{\text{av}} = 10 \text{mA (cw)} \); \( \varepsilon_{\text{norm}} = 10 \mu\text{m} \), \( P_{\text{dump}} \leq 50 \text{kW} \), Cost < 10M€
Footprint < 20*10m.

Kurt Aulenbacher: MESA: A new tool…

02.04.2009
ERL Facilities around the World

Planned Test Facilities and Installations:

**IHEP ERL, Beijing**
- 2 x 7 cell 1.3 GHz + DC Gun
- 10mA, 35MeV, 2ps

**BERLinPro**
- 3 x 7 cell cavities, 1.3 GHz
- 100mA, 50MeV, 1 mm mrad (norm), 2ps

**Peking ERL-FEL**
- 1 x 9 cell
- 60 pC, 30 MeV

**ALICE, Daresbury**
- 9 cell, 1.3 GHz
- 100 pC, 10 MeV, 100 µs bunch train

**2loop-CERL, KEK**
- 9 cell, 1.3 GHz cavities, 4 modules
- 77 pC, 245 MeV, 1-3 ps

**Brookhaven ERL**
- 1 x 5 cell, 704 MHz
- 0.7-5 nC, 20 MeV, CW
ERL Test Facility at CERN

Potential layout:

200-400 MeV ERL Layout
4 x 5 cell, 704 MHz
Ring: Dipole + Quadrupole Magnets

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
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<tbody>
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<tr>
<td>Cooling</td>
<td>air or water</td>
<td>depends on tunnel ventilation</td>
</tr>
</tbody>
</table>

Table 3.2: Main parameters of bending magnets for the RR Option.
Interaction Region: Synchrotron Radiation

Significant power: > 20 kW. Example Ring-Ring

First design of SR masks exists. But still require more detailed vacuum and background studies for such high SC radiation power.
Bypassing CMS: 20m distance to Cavern

c. 1.3 km long bypass
c. 300m long dispersion free area for RF installation
LINAC: Beam Dynamics Issues

- Has been studied for the linacs only
  - Arcs need to be included
  - Only analytics estimates used
- Continuous beam would trap ions in the linacs
  - This would lead to unstable beam
- One 10µs long gap in beam prevents long-term tracking
  - Rise time of instability during the train between gaps seems to be acceptable (10 turns)

- Full study needed
  - Arcs will make instability worse
  - Ions are not completely lost during one passage of the gap
  - But the frequency of the induced instability varies along the machine, which helps
## Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RR</th>
<th>LR</th>
<th>LR*</th>
<th>RR**</th>
</tr>
</thead>
<tbody>
<tr>
<td>e- energy at IP (GeV)</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>140</td>
</tr>
<tr>
<td>e- luminosity [10^32 cm^2 s^-1]</td>
<td></td>
<td></td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>polarization [%]</td>
<td>20</td>
<td>40</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>bunch population [10^9]</td>
<td></td>
<td>10</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>bunch length [mm]</td>
<td></td>
<td>60</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>e-beams IP beam size [m]</td>
<td></td>
<td>30</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>transv. emit. y_x [m]</td>
<td></td>
<td>30</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>bunch interval [ns]</td>
<td></td>
<td>25</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>transv. emit. y_x [m]</td>
<td></td>
<td>0.26</td>
<td>0.15</td>
<td>0.05</td>
</tr>
<tr>
<td>transv. emit. y_x [m]</td>
<td></td>
<td>0.15</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>full crossing angle [mrad]</td>
<td>1.0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>geometric reduction H [0.86, 0.91, 0.94]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>repetition rate [Hz]</td>
<td>N/A</td>
<td>N/A</td>
<td>10</td>
<td>N/A</td>
</tr>
<tr>
<td>beam pulse length [ms]</td>
<td>N/A</td>
<td>N/A</td>
<td>5</td>
<td>N/A</td>
</tr>
<tr>
<td>ER efficiency</td>
<td></td>
<td>94%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>average current [mA]</td>
<td>100</td>
<td>6.6</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td>tot. wall plug [MW]</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

### Notes
- The goal here is to develop a realistic set of parameters in both beam-beam, beam-beam, and beam-beam operational Versions for LHC and LHC versions.
- The planning here is to demonstrate that a beam with deuterons and lead (exists) and to also demonstrate that a beam with deuterons and lead (exists) can be demonstrated in both beam-beam, beam-beam, and beam-beam operational versions.
- Ring uses 1° as baseline: L2, Linac: clearing gap: L 23.
- RR = Ring - Ring
- LR = Linac - Ring

**LLL**
LHeC - Participating Institutes: A very rich collaboration
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LHeC Mini Workshop, 18th April 2013