Detectors for the LHeC and FCC-eh

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Baseline Design (Electron “Linac”)
LHeC CDR, July 2012 [arXiv:1206.2913]

Design constraint: power consumption < 100 MW → \( E_e = 60 \) GeV

- Two 10 GeV linacs,
- 3 returns, 20 MV/m
- Energy recovery in same structures

- LHeC ep lumi → \( 10^{34} \) cm\(^{-2}\) s\(^{-1}\)
  → ~100 fb\(^{-1}\) per year → ~1 ab\(^{-1}\) total
- e-nucleon Lumi estimates ~ \( 10^{31} \) (3\( \cdot \)10\(^{32} \)) cm\(^{-2}\) s\(^{-1}\) for eD (ePb)

- Similar schemes in collision with protons of 7 TeV (LHeC), 13 TeV (HE-LHeC) and 50 TeV (FCC-eh)
Physics Targets throughout Kinematic Plane

- Standalone Higgs programme

- Revolutionary proton PDF precision enhances LHC new physics sensitivity

- Elucidates low $x$ dynamics in $e p$ & $e A$

- 4 orders of mag. in kinematic range of nuclear structure

- No polarised targets
Detector Design: Philosophy

- Detector technologies evolve fast; current designs can only be indicative / based on current knowledge ... will change

- Conditions are relatively ‘easy’ ...
  ... fluences $\ll 10^5$ 1 MeV n cm$^{-2}$
  equiv (tiny fractions of HL-LHC)
  ... pile-up $\sim 0.1$ (cf 200 at HL-LHC)

- Current `baseline’ remains
  2012 CDR (with ongoing work in several areas)
    → Leans heavily on LHC (esp. ATLAS) technologies
      (but they are over-spec’ed for radiation hardness)
    → Was costed at CHF106M core cost

- Most challenging technology aspects are interaction region
  (synchrotron) and ER linac
• Dual dipole magnets (0.15 - 0.3 T) throughout detector region (|z| < 14m) bend electrons into head-on collisions

• Elliptical beampipe (6m x 3mm Be) accommodates synchrotron fan

• 3.5 T Superconducting NbTi/Cu solenoid in 4.6K liquid helium cryo.

Re-evaluating → reduce synchrotron?
Access to $Q^2=1$ GeV$^2$ in ep mode for all $x > 5 \times 10^{-7}$ requires scattered electron acceptance to 179°.

Similarly, need 1° acceptance in outgoing proton direction to contain hadrons at high $x$ (essential for good kinematic reconstruction).
Acceptance Requirements, Final States

- Elastic J/Ψ Photoproduction

- Higgs Production

\[ M_\phi = 120 \text{ GeV} \]
• Size 13m x 9m (c.f. CMS 21m x 15m, ATLAS 45m x 25m)
• 1° tracking acceptance in both forward & backward directions
• Forward & backward beam-line instrumentation integrated
Detector for ep at a Future Circular Collider

- Detector scales in size by up to $\ln(50/7) \sim 2$

- Double solenoid + Dipole

- Even longer track region to retain 1$^\circ$ performance
Inner Tracking:

an LHeC Design

... and an HE-LHC design

- 1° electron hits 2 tracker planes
- Forward direction allows particle flow with boosted jets
- Pixels + strips; Perfect application for HV-CMOS (cf EIC R&D programme)
Tracking Performance

From CDR → Central track $\Delta p_t/p_t^2 \to 6 \times 10^{-4}$ GeV$^{-1}$
Impact parameter resolution: → 10μm

More recently →
- Studies of HE-LHeC,
  Including services
- Evaluation of HF
tag performance (60% b,
30% c efficiency at 95%
light quark rejection) → Extend from 40 → 60cm (H→bb, cc)?
Barrel EM Calorimeter

- $-2.3 < \eta < 2.8$
- CDR accordion geometry baseline design
- 2.2mm lead + 3.8mm LAr layers
- Total depth $\sim 20 \, X_0$

- GEANT4 simulation of response to electrons at normal incidence

[cf ATLAS: $10%/\sqrt{E} + 0.35\%$]

- Extended version (HE-LHeC) with 30 $X_0$ designed
- Current re-evaluation of entire calorimeter in light of resolutions required for $H \rightarrow WW$, $bb$, Top etc ...
Beamline Instrumentation

z (m) 420 100 Electron Tagger -120
Proton Spectrometer Zero Degree Calorimeter -62 Photon Tagger
- Use Bethe-Heitler (as HERA), measurement based on photon

- Photons might be detected at $z = -120$ m after D1 proton bending dipole
- With sufficient aperture through Q1-Q3 magnets, 95% geometrical acceptance
- Signal via Cerenkov from synchrotron absorber coolant? $\rightarrow$ 1% lumi measurement? $\rightarrow$ Synchrotron OK?
Low Angle Electron Tagging

- Reinforce luminosity measurement
- Tag $\gamma p$ for measurements and as background to DIS

- Acceptances ~ 20-25% at 3 different locations studied

- 62m is most promising due to available space and synchrotron radiation conditions
Methods for Diffraction

... old slide from diffraction at HERA

Signatures and Selection Methods

Scattered proton in Leading Proton Spectrometers (LPS)

`Large Rapidity Gap` (LRG) adjacent to outgoing (untagged) proton

Limited by statistics and p-tagging systematics

Limited by p-diss systematics

Partially still true for LHeC (but proton tagging technology got better and kinematics make rapidity gap methods harder)
Rapidity Gap Selection with LHeC Kinematics

- $\eta_{\text{max}} \propto \xi (= x_{IP})$ correlation determined entirely by proton beam energy ...
  [LHeC proton kinematics same as LHC]

- LHeC cut around $\eta_{\text{max}} \sim 3$ selects events with $x_{IP} < 10^{-3}$ (cf $x_{IP} < 10^{-2}$ at HERA), but misses lots of diffractive physics at largest dissociation masses, $M_X$
LHeC Forward Proton Spectrometer

- Proton spectrometer is a copy of FP420 (proposal for low $\xi$ Roman pots at ATLAS / CMS - currently being revisited)

- Requires access to beam though cold part of LHC

- Acceptances under study with HL-LHC optics

233 m
Leading Neutrons

- Crucial in eA, to determine whether nucleus remains intact e.g. to distinguish coherent from incoherent diffraction

- Crucial in ed, to distinguish scattering from proton or neutron

- Possible “straight on” space at z ~ 100m

- For technology, learn from LHC
Summary

- CDR 2012

- Since then 1) Possibility of $10^{34}$ cm$^{-2}$ s$^{-1}$ → new environment
2) LHC Higgs discovery → new physics focus
3) Longer term perspective of HE-LHeC / FCC-eh

- Current ongoing work: optimize w.r.t. precision physics, H, t ...
re-evaluation of tracking & calorimetry, interaction region

- Next goal ...
1) Update CDR (physics, technical) → “The LHeC at High Luminosity” converging at workshop in October 2019
LHeC Context

LHeC: 60 GeV electrons x LHC protons & ions → $10^{34}$ cm$^{-2}$ s$^{-1}$ → Simultaneous running with ATLAS / CMS in HL-LHC period

FCC-ep: 60 GeV electrons x 50 TeV protons from FCC

Proposed energy frontier high luminosity ep / eA facility → TeV scale physics at $10^{34}$ cm$^{-2}$s$^{-1}$
LHeC Timeline

Long Term LHC Schedule

PHASE I Upgrade
ALICE, LHCb major upgrade
ATLAS, CMS major upgrade

PHASE II Upgrade
ATLAS, CMS major upgrade

- LHC Injector Upgrade
- Heavy Ion Luminosity from $10^{27}$ to $7 \times 10^{27}$

HL-LHC, pp luminosity from $2 \times 10^{34}$ (peak) to $5 \times 10^{34}$ (levelled)

Not defined ... but makes best sense in parallel with HL-LHC ... schedule extends to 2040; LS4, LS5 are possibilities
Where could the LHeC be built?

- Default design is 1/3 at Point 2 (currently ALICE)
- Point 8 (currently LHCb) has also been considered
**Tracking:** four slim-edge 3D pixel sensor planes per station (ATLAS IBL)
- Pixel sizes 50x250 μm
- 14° tilt improves x resolution (hence $\xi$)
  \[ \delta x = 6 \, \mu m, \, \delta y = 30 \, \mu m \]
- Trigger capability

**Timing:** 4x4 quartz bars at Cerenkov angle to beam. Light detected in PMTs
  \[ \rightarrow \text{expected resolution 25ps} \]

But we can’t just put them everywhere!
- Locations of pots restricted by beam elements
- Scattered proton trajectories blocked by collimators etc
- Sensitive detectors can’t approach arbitrarily close to beam
Acceptance Depends on Location and Orientation of Pot and on beam optics

- In ATLAS case, complementarity between ATLAS ALFA (vertical approach) and AFP (horizontal approach)
- AFP acceptance for inelastic diffraction with $\xi \sim 0.02$
- Current situation is result of prolonged study, also with machine group, and optimisation / compromise on beam optics.
Secondary Vertex Tagging

HFL Tagging

Uta Klein & Daniel Hampson

→ Realistic and conservative HFL tagging within Delphes realised, and dependence on vertex resolution (nominal 10 μm) and anti-kt jet radius studied
→ Light jet rejection very conservative, i.e. factor 10 worse than ATLAS
→ used in full LHeC analysis and for FCC-eh extrapolations

Beauty
60%

Charm
30%
CDR Muon System

Baseline: Provides tagging, but not momentum measurement (under review in view of Higgs physics programme)

- Angular coverage → $1^\circ$ vital eg for elastic $J/\Psi$
- Technologies used in LHC GPDs and their upgrades (more than) adequate

[2 or 3 Superlayers]

[Drift tubes / Cathode strip chambers → precision
Resistive plate / Thin Gap chambers → trigger + 2nd coord]
- **Barrel HAD calorimeter**, outside coil
  → 4mm Steel + 3mm Scintillating Tile
  → 7-9 $\lambda$, $\sigma_{E}/E \sim 30%/\sqrt{E} + 9\%$ [~ ATLAS]

- **Forward end-cap** silicon + tungsten, to cope with highest energies & multiplicities, radiation tolerant EM
  → 30$X_0$, Had $\rightarrow 9\lambda$

- **Backward end-cap**
  Pb+Si for EM (25$X_0$)
  Cu+Si for HAD (7$\lambda$)
Leading Neutrons: Solutions from LHC
... needs to be compact and radiation-hard

- ALICE, ATLAS, CMS all use tungsten absorber + quartz fibres (Cerenkov).
- LHCf uses tungsten + plastic scintillator in special runs
- Improve hadronic response with dual quartz / scintillator?
- Longitudinal segmentation essential to distinguish neutrons from photons.