From LHeC to FCC-he Detectors

P.Kostka, A.Polini
on behalf of the LHeC Study Group

http://cern.ch/lhec

CDR: “A Large Hadron Electron Collider at CERN”
LHeC Study Group, [arXiv:1206.2913]
e± Beam Options: RR and LR

- **Ring-Ring**
  - $e^\mp p$ and $e^\mp A$ (A=Pb, Au, …) collisions
  - More “conventional” solution, like HERA, no difficulties of principle - at first sight - but constrained by existing LHC in tunnel
  - polarization 40% with realistic misalignment assumptions

- **Linac-Ring (default)**
  - $e^\mp p$ and $e^\mp A$ (A=Pb, Au, …) collisions, polarized $e^-$ from source, somewhat less luminosity for $e^+$
  - New collider type of this scale, Energy Recovery Linac
Baseline: Energy Recovery Linac

- Linac-Ring design employs two 1km long Linac’s, with energy recovery
  - Novel new accelerator design
  - Default option due to reduced impact on the LHC schedule (compared to RR design)
  - Lower luminosity for $e^+$ running ($e^-$ - a few $10^{34}$ cm$^{-2}$s$^{-1}$ achievable)

### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity [10$^{33}$cm$^{-2}$s$^{-1}$]</td>
<td>1-10**</td>
</tr>
<tr>
<td>Detector acceptance [deg]</td>
<td>1</td>
</tr>
<tr>
<td>Polarization [%]</td>
<td>90</td>
</tr>
<tr>
<td>IP beam sizes [μm]</td>
<td>7</td>
</tr>
<tr>
<td>Crossing angle [mrad]</td>
<td>0</td>
</tr>
<tr>
<td>e- L* [m]</td>
<td>30</td>
</tr>
<tr>
<td>Proton L* [m]</td>
<td>15</td>
</tr>
<tr>
<td>e- beta$^*$$_{x,y}$ [m]</td>
<td>0.12</td>
</tr>
<tr>
<td>Proton beta$^*$$_{x,y}$ [m]</td>
<td>0.1</td>
</tr>
<tr>
<td>Synchrotron power [kW]</td>
<td>22</td>
</tr>
</tbody>
</table>

** high luminosity achievable according to recent estimates

With the Higgs discovery and measured cross section $\sigma \sim 200$fb there is a striking option to make the LHeC a clean Higgs factory with maximum luminosity
The Interaction Region

3 beam interaction region
Optics compatible with LHC running and $\beta^*=0.1\text{m}$
Head-on collisions achieved via long dipole
across interaction region
→ Dipole in main detector
→ High synchrotron radiation load
Beam Pipe Considerations

- Circular-Elliptical beam-pipe design
  - Beryllium 2.5-3.0 mm wall thickness
  - Central beam pipe ~ 6 meters
  - TiZrV NEG coated
  - Wall protected from primary SR (upstream masks)
  - Minimised end flanges, minimised supports
  - Optimisation needed - R&D
- High x and high $Q^2$: few TeV HFS scattered forward:
  - → Need forward calorimeter of few TeV energy range down to 1\(^0\)
- Mandatory for charged currents where the outgoing electron is missing
- Scattered electron:
  - → Need very bwd angle acceptance for accessing the low $Q^2$ and high $y$ region
Detector Requirements from Physics

• **High resolution tracking system**
  – excellent primary vertex resolution
  – resolution of secondary vertices down to small angles in forward direction for high x heavy flavor physics and searches
  – precise $p_t$ measurement matching to calorimeter signals (high granularity), calibrated and aligned to 1 mrad accuracy

• **The calorimeters**
  – electron energy to about $10\% / \sqrt{E}$ calibrated using the kinematic peak and double angle method, to permille level
    
    Tagging of $\gamma$'s and backward scattered electrons - precise measurement of luminosity and photo-production physics
  – hadronic part $40\% / \sqrt{E}$ calibrated with $p_{t_e} / p_{t_h}$ to 1% accuracy
  – Tagging of forward scattered proton, neutron and deuteron - diffractive and deuteron physics

• **Muon system, very forward detectors, luminosity measurements**
Baseline Detector

- High acceptance Silicon Tracking System ~1°
- Liquid Argon Electromagnetic Calorimeter (or Pb/Scintillator)
- Fe-Scintillator Hadronic Calorimeter (magnet return flux)
- Forward Backward Calorimeters: Si/W Si/Cu ...
Detector Magnets: Solenoid and Dipoles

- **Baseline:** Solenoid (3.5 T) + dual dipole 0.3 T (Linac-Ring Option)
  Both magnets (may be) embedded into EMC LAr Cryogenic System
  - Large coils (double solenoid): Containing full calorimeter, precise muon measurement, large return flux
- **Small coil:** Cheaper, less iron for return flux, solenoid and dipoles conveniently within the same cold vacuum vessel, but no muon measurement
LHeC Detector Overview

- Forward / backward asymmetry reflecting beam kinematic / energy flow
- Present size: 14m x 9m (c.f. CMS 21m x 15m, ATLAS 45m x 25 m)
- e/γ taggers ZDC, proton spectrometer integral to design from outset system providing tagging, no independent momentum measurement
Forward Energy and Acceptance

RAD: 60 GeV electron x 7 TeV proton

CHARM: 60 GeV electron x 7 TeV proton

DIFF: 60 GeV electron x 7 TeV proton

NRAD: 60 GeV electron x 7 TeV proton

→ Highest acceptance desirable
Fwd/Bwd Calorimeters

- Forward/Backward Calorimeters
- Forward FEC + FHC: tungsten high granularity; Si (rad-hard)
  high energy jet resolution
  \( \text{FEC: } \sim 30 X_0; \text{ FHC: } \sim 8-10 \lambda_I \)
- Backward BEC + BHC:
  need precise electron tagging; Si-Pb, Si-Fe/Cu (\( \sim 25 X_0, 6-8 \lambda_I \))
- GEANT4 simulation
  containment, multi-track resolution (forward)
  \( e^+ \) tagging/E measurement (backward)

Highest energies in forward region
Radiation hard
High Granularity
Linearity
Hadronic Calorimeter

• Baseline design
  – HAC iron absorber (magnet return flux)
  – scintillating plates (similar to ATLAS TILE CAL)
  – Interaction lengths of ~ 7-9 $\lambda_I$

<table>
<thead>
<tr>
<th>Tile Rows</th>
<th>Height of Tiles in Radial Direction</th>
<th>Scintillator Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>97 mm</td>
<td>3 mm</td>
</tr>
<tr>
<td>4-6</td>
<td>127 mm</td>
<td>3 mm</td>
</tr>
<tr>
<td>7-11</td>
<td>147 mm</td>
<td>3 mm</td>
</tr>
</tbody>
</table>

• GEANT4 + FLUKA simulations
  – containment, resolution, combined HAC & EMC response
  – solenoid/dipoles/cryostat in between

Impact of Al

Electrons

Pions

$\theta=90^\circ$

$\theta=70^\circ$

FCC Study Kickoff Meeting

14 February 2014
Baseline Solution:
Muon system providing tagging, no independent momentum measurement
Momentum measurement done in combination with inner tracking
Present technologies in use in LHC exp. sufficient (RPC, TGC, MDT, mMegas etc.)
FCC Study Kickoff Meeting

Linac-Ring:
- LHeC ERL + FCC-hh
- $e^\mp (60 \text{ GeV})$ p/A at 50 TeV

Design choice: beam parameters as available from $hh$ and $ee$
- Max. $e^\pm$ beam current at each energy determined by 50 MW SR limit.
- 1 physics interaction point, optimization at each energy

<table>
<thead>
<tr>
<th>collider parameters</th>
<th>$e^\pm$ scenarios</th>
<th>protons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$e^\pm$ (polarized)</td>
<td>$e^\pm$</td>
</tr>
<tr>
<td>beam energy [GeV]</td>
<td>80</td>
<td>120</td>
</tr>
<tr>
<td>luminosity [$10^{34}\text{cm}^{-2}\text{s}^{-1}$]</td>
<td>2.3</td>
<td>1.2</td>
</tr>
<tr>
<td>bunch intensity [$10^{11}$]</td>
<td>0.7</td>
<td>0.46</td>
</tr>
<tr>
<td>#bunches per beam</td>
<td>4490</td>
<td>1360</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>152</td>
<td>30</td>
</tr>
<tr>
<td>$\sigma_{xy}^*$ [micron]</td>
<td></td>
<td>4.5, 2.3</td>
</tr>
</tbody>
</table>

FCC-he design challenges

Integration aspects, machine detector interface
- Synchrotron radiation
- Large polar angle acceptance

IR optics & magnets with 3 beams
- Crossing scheme
- Detector integrated dipole, final SC quadrupoles, crab cavities,

Concurrent operation of $e^\pm h$ with $hh$ or/and $e^+e^-$ operation?

Relevant expertise available worldwide and potential synergies:
⇔ HERA, eRHIC, MEIC, HIAF-EIC,...

Alternative option for $eh$ collisions in connection with FCC-$hh$:
- Potential reuse of an energy recovery linac (ERL) that is being studied in the frame of the LHeC study.

Ring-Ring: FCC-he
- $e^\mp$ (max) 175 GeV + p/A 50 TeV
Linac-Ring
Forward calorimeter containment up to few $10^{th}$ TeV down to $1^0$

increase the calorimeter depth compared to LHeC (especially in forward region)

Ring-Ring
Kinematic coverage can also be achieved by lowering $E_\theta$ (goes squared to lower $Q^2$) and lowering $E_p$ (accesses larger $x$)

e/A interactions - splash of particles produced - to be measured
From the LHeC to the FCC

• Interaction region:
  – Assume similar interaction region as for LHeC
  – dipole field across the whole detector
  – $e^\pm$ syn radiation $\rightarrow$ elliptical beampipe

• Detector:
  – Higher momenta/energies $\rightarrow$ Larger $B L^2$, Larger calorimetry
  – Large acceptance over $\eta$
  – Bunch spacing ($25\text{ns} \rightarrow 5\text{ns}$), (pile up less of a problem in $ep$)

• Beam Pipe Design
  – low $X_0$, $\lambda I$ material, stable, capable for $1^0$ tracks
  – allowing low $p_T$ particle measurement
  – R&D needed (new ideas)
The FCC-he Detector Scheme - LR

- A very first arrangement based on the LHeC design using LR constraints (dipoles)
- Forward calorimeter containment up to few 10^{th} TeV down to 1^{\circ}
- Forward/backward taggers not shown but also present (FPS, ZDC, e γ taggers, e polarimeter)
An arrangement based on the LHeC design with a large solenoid

- Less material in front of HAC calorimetry

Double solenoid system (second solenoid not to scale):

- ample return field region for independent (muon) momentum measurement
- Lightweight structure
The FCC-he enlarges further the LHeC physics program

- DIS ep and eA in the widest x-Q\(^2\) range
- Very precise Higgs physics (Can also explore H \(\rightarrow\) HH)
- …

The detector:
- A very preliminary draft has been presented
- An FCC-he detector appears feasible using todays technologies
- The detector design will benefit from coming technology progress
- Full simulation being setup based on DD4hep/DDG4 toolset
- The FCC-he detector provides a high level of synergy withing HEP and the FCC in some of the challenges
Backup
Extensions LHeC detector:
- Independent momentum measurement
- Large solenoid
- Dual Coil System (homogeneous return field)
- Forward Toroid System
First feasibility studies

- Cross-sections for CC backgrounds in fb for $E_e=60, 120, 150$ GeV

<table>
<thead>
<tr>
<th>Processes</th>
<th>$E_e = 60$ GeV</th>
<th>$E_e = 120$ GeV</th>
<th>$E_e = 150$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma$(fb)</td>
<td>$\sigma_{eff}$(fb)</td>
<td>$\sigma$(fb)</td>
</tr>
<tr>
<td>$e^-p \to \nu_e b\bar{b}b\bar{b}j$</td>
<td>0.086</td>
<td>0.022</td>
<td>0.14</td>
</tr>
<tr>
<td>$e^-p \to \nu_e b\bar{c}c\bar{c}j$</td>
<td>0.12</td>
<td>$1.7 \times 10^{-5}$</td>
<td>0.36</td>
</tr>
<tr>
<td>$e^-p \to \nu_e c\bar{c}c\bar{c}j$</td>
<td>0.20</td>
<td>$1.0 \times 10^{-6}$</td>
<td>0.24</td>
</tr>
<tr>
<td>$e^-p \to \nu_e b\bar{b}j\bar{j}j$</td>
<td>26.1</td>
<td>$3.9 \times 10^{-3}$</td>
<td>54.2</td>
</tr>
<tr>
<td>$e^-p \to \nu_e c\bar{c}j\bar{j}j$</td>
<td>29.6</td>
<td>$9.5 \times 10^{-5}$</td>
<td>66.9</td>
</tr>
<tr>
<td>$e^-p \to \nu_e j\bar{j}j\bar{j}j$</td>
<td>823.6</td>
<td>$4.1 \times 10^{-5}$</td>
<td>1986</td>
</tr>
</tbody>
</table>

Results assume 70% b-tagging efficiency, 0.1 (0.01) fake rates for c (light) jets

Plots for $E_e=60$ GeV (very similar for 120,150 GeV)

Despite large beam energy imbalance, b-jets are relatively central

Scattered quark is more forward in signal $\rightarrow$ good discriminant!
Tracker Simulation


- Silicon: compact design, low budget material, radiation hard

transverse momentum resolution
\[ \frac{\Delta p_t}{p_t^2} \to 10^{-3} \text{ GeV}^{-1} \]

impact parameter resolution
\[ \to 10 \mu m \]

FCC Study Kickoff Meeting 14 February 2014
Electromagnetic Calorimeter

- Simplified design simulation w.r.t. ATLAS
- LAr Calorimeter: good energy resolution, stable performance
- Simulation results compatible with ATLAS
- Warm (Pb/Sci) option also investigated
- $30X_0$ ($X_0$(Pb)=0.56 cm; 20 layers)