EIC Detectors: An Overview

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Electromagnetic Interactions with Nucleons and Nuclei EINN2017
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Electron-Ion Collider EIC

Polarized ep, eA collider

\[ \sqrt{s} = 35 - 180 \text{ GeV} \]
\[ \text{Luminosity} = 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]

Two possible sites

Brookhaven -> eRHIC
Jefferson lab -> JLEIC

Scientific goals

Study of perturbative & non-perturbative QCD
Tomography (including transverse dimension) of the nucleon, nuclei
Understanding the nucleon spin
Discovery of gluon saturation...

Construction to start in 2025

Community optimistic about prospect of realization
Quantum Chromodynamics QCD

Theory of hadronic interactions (no doubts!)

Has been validated in countless experiments (LEP, HERA, Tevatron, LHC...) where perturbative calculations are possible (high energy -> small coupling)

A deeper understanding of QCD requires exploring

The non-perturbative regime of the theory

3D tomography of the nucleon and nuclei
    Generalized Parton Distributions (GPDs)
    Transverse Momentum Distributions (TMDs)

Contributions to the nucleonic spin
Confinement
Nuclear modifications of the parton density functions
Non-linear evolution (saturation)
....

These questions are to be addressed by the EIC
## Measurements at the EIC

<table>
<thead>
<tr>
<th>Physical quantity</th>
<th>Process</th>
<th>Measurement challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure functions $F_2$, $F_L$ Nuclear structure functions</td>
<td>Inclusive scattering</td>
<td>Electron identification, background rejection, luminosity</td>
</tr>
<tr>
<td>Spin structure functions</td>
<td>Inclusive scattering</td>
<td>+ polarization</td>
</tr>
<tr>
<td>Gluon density</td>
<td>Charm, dijet production ...</td>
<td>Secondary vertex, pion/kaon separation, hadronic jets</td>
</tr>
<tr>
<td>Generalized Parton Distributions GPDs</td>
<td>Deeply Virtual Compton Scattering</td>
<td>Forward proton, e, γ measurements background rejection</td>
</tr>
<tr>
<td>Transverse Momentum Distributions TMDs</td>
<td>Semi-inclusive Deep Inelastic Scattering</td>
<td>Pion/kaon separation</td>
</tr>
<tr>
<td>Nuclear PDFs</td>
<td>Scattering on nuclei</td>
<td>Nuclear fragments</td>
</tr>
<tr>
<td>Many more</td>
<td></td>
<td></td>
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</tbody>
</table>

J. Repond - Imaging Calorimetry
Scattered electron in Neutral Current DIS

At low $y$, electron energy is a poor estimator of $x$

Electron angle good estimator of $Q^2$

$\frac{\Delta x}{x} = \frac{1}{y} \frac{\Delta E_e}{E_e}$

Need large coverage and good electron ID
At low $y$, quark energy good estimator of $x$

$$\frac{\delta x}{x} = \frac{1}{1 - y} \frac{\delta E_q}{E_q}$$

**Good hadron energy resolution essential**
Requirements for EIC Detectors

- **Vertex detector**
  - Event vertex, secondary vertices, track impact parameter

- **Central tracker and solenoid**

- **Calorimeter**
  - TOF or Cerenkov
  - Roman pots
  - 0° calorimeter
  - Polarimeter

- **Electron identification and measurement**
  - $-4 < \eta < +4$

- **Hadronic jet measurement**
  - Excellent energy resolution, kinematic reconstruction

- **Pion/kaon/proton separation**
  - For most of the solid angle PID needed for $p < 7$ GeV/c
  - In forward direction needed for $p < 50$ GeV/c

- **Forward proton/ion detection and measurement**
  - Large acceptance for momenta up to almost the beam energy

- **Forward neutron detection and measurement**
  - Excellent energy and angle measurement
The HERA Detectors I

Multi-purpose $4\pi$ detector with

Charged particle tracking

Si - $\mu$VTX
Central drift chamber

Liquid Argon calorimeter

\[
\frac{\sigma_{em}}{E} = \frac{12\%}{\sqrt{E\,(GeV)}}
\]
\[
\frac{\sigma_{had}}{E} = \frac{50\%}{\sqrt{E\,(GeV)}}
\]

Rear Pb-scintillator plug

\[
\frac{\sigma_{em}}{E} = \frac{7.5\%}{\sqrt{E\,(GeV)}}
\]

Muon chambers and more...
The HERA Detectors II

Multi-purpose $4\pi$ detector with

- Charged particle tracking
  - Si - $\mu$VTX
  - Central drift chamber
- Uranium-Scintillator calorimeter
  \[
  \frac{\sigma_{em}}{E} = \frac{18\%}{\sqrt{E(GeV)}}
  \]
  \[
  \frac{\sigma_{had}}{E} = \frac{35\%}{\sqrt{E(GeV)}}
  \]
- Muon chambers and more...

Note: both detectors are asymmetric around the interaction point
have no particle ID
limited acceptance in forward direction
Choices I

**General purpose detector** (such as ATLAS and CMS at the LHC or H1/ZEUS at HERA)

- Advantage of 1 device for all, better background rejection
- More challenging to design

or

**Specialized detectors** (such as ALICE and LHCb at the LHC)

- Potentially better for the measurement of a particular process
- Less boundary conditions – easier to design

or

**Mixture of both**

Personally, I would opt for one (1) state-of-the-art detector
Choices II

Asymmetric versus symmetric detector

Beam energies will be asymmetric, i.e. more energy in the hadron direction

HERA experiments reduced the calorimeter depth in the electron direction
(later H1 added a hadron calorimeter behind their backward end-plug calorimeter)

With high luminosity, both scattered electrons and hadrons will go everywhere

An asymmetric detector results in an asymmetric force on the solenoid

No reason to go asymmetric, apart from special very forward detectors

From E.C. Aschenauer

15 GeV $e^-$ x 250 GeV p: $e^-$, $\gamma$, $h^-$
Choices III

Cost

Some detectors are cheap (e.g. RPCs)
Some are more expensive (e.g. Silicon)

However, the cost is not constant with time (e.g. Silicon and CMS)

In the early stages, cost should not be overemphasized

An optimal detector means maximum use of luminosity

From H. Sadrozinski (2001)
Popular choices for the Major Subsystems

**Vertex detector** -> Identify event vertex, secondary vertices, track impact parameters
   Silicon pixels, e.g. MAPS

**Central tracker** -> Measure charged track momenta
   Drift chamber, TPC + outer tracker or Silicon strips

**Forward tracker** -> Measure charged track momenta
   GEMs, Micromegas, or Silicon strips

**Particle Identification** -> pion, kaon, proton separation
   Time-of-Flight or RICH + dE/dx in tracker

**Electromagnetic calorimeter** -> Measure photons (E, angle), identify electrons
   Crystals (backward), Shashlik or Scintillator/Silicon-Tungsten

**Hadron calorimeter** -> Measure charged hadrons, neutrons and $K_L^0$
   Plastic scintillator or RPC + steel

**Muon system** -> Identify muons as punch-throughs
   Plastic scintillator or RPCs + yoke or none

+ Beam pipe, Solenoid, very forward and backward detectors
4 Detector Concepts for the EIC

Brookhaven concept: BEAST

Jefferson lab concept: JLEIC

sPhenix -> ePhenix

Argonne concept: SiEIC
BEAST (Brookhaven eA Solenoidal Tracker)

From A. Kiselev
BEAST: Tracker I

Silicon vertex detector

Inspired by the ALICE ITS (inner tracking system) design (upgrade for LS2 2019-2020)

Based on MAPS with 20 x 20 $\mu$m$^2$ pixels
  -> Monolithic Active Pixel Sensors
  -> Incorporate a matrix of charge collection diodes (pixels)
    + electronics (signal amplification, digitization, and 0 suppression)
  -> only hit/no hit information!

Barrel: 4 layers with 0.3% $X_0$ each
Endcap: 3 disks
BEAST: Tracker II

Central TPC

2 m long, $R_{\text{inner/outer}} = 22.5/77.5$ cm
Gas mixture: e.g. Argon:Freon:Isobutane = 95:3:2
5 – 6 % $X_0$ field cage in barrel + 15% $X_0$ at endcaps
GEM readout: pads 5 mm long, assume 50 $\mu$m resolution

+ Micromegas

Inside and outside the TPC
For track seeding
Number of layers to be determined

Endcap

GEM: 3 disks

Superconducting Solenoid

3 Tesla (+- 4%) in TPC region
Outside the electromagnetic calorimeter
BEAST: Calorimetry

Electromagnetic calorimeter

Very backward pseudo-rapidities ($\eta < -2$)

$\text{PbWO}_4$ crystals with $\sim 2\%/\sqrt{E}$ energy resolution

Barrel and forward region ($-2 < \eta < 3.5$)

Tungsten powder + scintillating fiber with $7 - 10\%/\sqrt{E}$

Hadron calorimeter

Only in the forward (measure hadrons) and backward (identify electrons) direction

Scintillator plate + lead absorber with $\sim 50\%/\sqrt{E}$

No hadron calorimeter in the barrel region
Comment to barrel hadron calorimeter

BEAST

Does not feature a barrel hadron calorimeter

Argument

Not needed
Fraction of jet energy carried by neutral hadrons (neutrons and $K_L^0$) is small ~10%
Charged hadrons measured by tracker

However

The EIC is a precision machine (at the 1% level)
$E_{\text{neutral}}$ is small in average, but large fluctuations
Electron ID is needed in the barrel region and is helped by an hadron calorimeter
Kinematic reconstruction needs all hadrons (double angle)
  -> In particular for charged current events (no electron)
  -> At medium/large x (where the electron method fails)
Background rejection requires hermeticity
BEAST: Particle Identification

Low momenta \((p < 1 \text{ GeV/c})\)

\(dE/dx\) in tracker or time-of-flight (with moderate resolution)

Intermediate momenta \((1 < p < 3 - 4 \text{ GeV/c})\)

Ring Imaging Cerenkov with Aerogel \((n \approx 1.05)\)

High moment \((10 < p < 50 \text{ GeV/c})\)

Ring Imaging Cerenkov with gas radiator
Requires about 1m depth
(to produce enough light)
Only needed and practical in the forward direction
The JLEIC Concept

Central detector

- Similar concept to BEAST
  - Vertex detector
  - Central tracker
  - Forward tracking
  - Cerenkov detectors
  - Electromagnetic calorimeters
  - Hadron calorimeter in the forward direction

- Muon chambers

Particular emphasis on

- Forward and backward detectors
  (other concepts could do this too, but JLEIC put more effort into this)
JLEIC: Electron Direction

$0^0$ angle photon calorimeter

- $\rightarrow$ Luminosity via Bethe-Heitler Process

Low-$Q^2$ tagger

- $\rightarrow$ Measurement of low-energy electrons

Laser + Compton Photon calorimeter + Electron tracking detector

- $\rightarrow$ Polarization measurement
JLEIC: Proton/ion Direction

Dipole magnet

Provides analyzing power to forward fragments
Requires magnetic cloak to shield stored electron beam (being developed by Stonybrook)

GEM trackers

Inside dipole

Roman pots further down the beam line

Acceptance close to 100% for diffractive peak ($x_L > 0.98$)

$0^0$ calorimeter further down

Measure forward neutrons
Large acceptance
The ePHENIX Concept

Evolution

PHENIX -> sPHENIX -> ePHENIX
(CD-4 by 2023)

Superconducting solenoid

Scavenged from Babar: 1.5 T

Central detector

Compact-TPC
RICH + DIRCs
ECAL: Tungsten-fiber shashlik (12%/√E)
Barrel HCAL: Scintillator-steel (100%/√E)

Forward detection

Crystal calorimeters, Roman pots, 0° calorimeters

-> Could be ready on Day 1 of the EIC Physics program
### List of particles

**MC Hadron level**

#### DIS event

<table>
<thead>
<tr>
<th>Particle ID</th>
<th>$P_x$</th>
<th>$P_y$</th>
<th>$P_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 (e⁻)</td>
<td>-0.743</td>
<td>-0.636</td>
<td>-4.842</td>
</tr>
<tr>
<td>321 (K⁺)</td>
<td>0.125</td>
<td>0.798</td>
<td>6.618</td>
</tr>
<tr>
<td>-211 (π⁻)</td>
<td>0.232</td>
<td>0.008</td>
<td>3.776</td>
</tr>
<tr>
<td>-211 (π⁻)</td>
<td>0.151</td>
<td>-0.007</td>
<td>4.421</td>
</tr>
<tr>
<td>211 (π⁺)</td>
<td>0.046</td>
<td>0.410</td>
<td>2.995</td>
</tr>
<tr>
<td>111 (π⁰)</td>
<td>-0.093</td>
<td>0.048</td>
<td>1.498</td>
</tr>
<tr>
<td>2112 (p)</td>
<td>0.115</td>
<td>-0.337</td>
<td>31.029</td>
</tr>
<tr>
<td>211 (π⁺)</td>
<td>0.258</td>
<td>0.145</td>
<td>6.336</td>
</tr>
<tr>
<td>310 (K_S⁰)</td>
<td>0.385</td>
<td>-0.408</td>
<td>3.226</td>
</tr>
</tbody>
</table>

**Detector output**

Wouldn’t it be nice to have the same information?
Argonne: SiEIC: The 5D Concept

The idea

Measure \((E,x,y,z,t)\) for every hit in tracker + CAL

Silicon pixel vertex + **strip tracker**

Imaging calorimeter

Superconducting solenoid (3T)

Forward gaseous RICH

Forward dipole + cloak or toroid w/out cloak

Forward silicon disks

Forward calorimetry

Backward silicon disks

Backward crystal calorimeter

Particle identification (\(\pi - K - \) proton separation)

Particle momenta < 10 GeV/c for most of the solid angle from tracker + calorimeter

Requires **silicon sensors with time resolution of about 10 ps**

Eliminates

The need for preshower counters, TRDs, TOF or Cerenkov (in front of the calorimeter), muon chambers (in back of calorimeter)
Imaging Calorimetry

Replace

Tower structure with very fine granularity (lateral and longitudinally)
Few 1,000 channels -> few 10,000,000 channels
Option to reduce resolution on single channels to 1 – 2 bits (digital readout)

Technologies developed in past decade

Silicon sensors with 1 x 1 cm², 0.25 x 0.25 cm² and 0.16 cm² pixels
Scintillator strips (4.5 x 0.5 cm²) or scintillator pads (3 x 3 cm²)
Resistive Plate chambers with 1 x 1 cm² pads
Micromegas and GEMs with 1 x 1 cm² pads

Advantages

Particle ID (electron, muon) almost trivial
Software compensation possible (improvement in resolution)
Longitudinal leakage corrections (using information from last layers)
Monitoring of gain (using track segments)
Identification of underlying events (low p_T background)

Application of Particle Flow Algorithms (PFAs)
Particle Flow Algorithms

Attempt to measure the energy/momentum of each particle in a hadronic jet with the detector subsystem providing the best resolution.

<table>
<thead>
<tr>
<th>Particles in jets</th>
<th>Fraction of energy</th>
<th>Measured with</th>
<th>Resolution $[\sigma^2]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged</td>
<td>65 %</td>
<td>Tracker</td>
<td>Negligible</td>
</tr>
<tr>
<td>Photons</td>
<td>25 %</td>
<td>ECAL with 15%/$\sqrt{E}$</td>
<td>0.07$^2 E_{jet}$</td>
</tr>
<tr>
<td>Neutral Hadrons</td>
<td>10 %</td>
<td>ECAL + HCAL with 50%/$\sqrt{E}$</td>
<td>0.16$^2 E_{jet}$</td>
</tr>
<tr>
<td>Confusion</td>
<td>If goal is to achieve a resolution of 30%/$\sqrt{E}$</td>
<td>$\leq 0.24^2 E_{jet}$</td>
<td></td>
</tr>
</tbody>
</table>

PANDORA PFA based on ILD detector concept

**Factor ~2 better jet energy resolution than previously achieved.**

**EIC environment:** particularly suited for PFAs, due to low particle multiplicity and low momenta.
Ultra-fast Silicon Sensors

Needed in

Calorimeter and tracker for Particle ID
(π - K – p separation)
Resolution of 10 ps -> separation up to ~ 7 GeV/c

Current status

Being developed based on the LGAD technology
Best timing resolution about 27 ps

Future

Further improvements ongoing
Interest in developing ultra-fast CMOS sensors (addition of amplification layer)

Time distribution system

Initiated development and tests at Argonne
Silicon Tracker: Considering tilted sensors

Non Tilted Sensor Planes

Tilted Sensor Planes
More hits, 25% less material (in $X_0$)

Taken from Peter Kostka and Alessandro Polini (LHeC studies)
SiEIC in Simulation

Starting point

SiD detector concept developed by ILC community

SiEIC

Some initial modifications from SiD

- Longer barrel, lower B-field, shallower calorimeters

No performance tuning yet
(detector optimized for $|\eta| < 3.0$)

Simulation

Entire chain available
- EG, GEANT4, digitization, reconstruction, analysis

Introduced DD4Hep
- One geometry file for sim., dig., rec., analysis

Ongoing replacement of parts difficult to maintain/develop
- digitization, tracking -> generic tracking

(full JLEIC det. sim., dig. and rec. to be available soon)
Conclusions

EIC environment/physics poses specific challenges

Detection of forward proton/neutron/ions
Measurement of scattered electron at low angles
Particle identification (pion – kaon – proton) over large solid angle
Kinematic reconstruction of charged current events (no scattered electron)

Challenges being addressed by various concepts being developed

BEAST, sPHENIX, JLEIC; SiEIC
Thanks to

Elke Aschenauer, Alexander Kiselev, Pawel-Nadel Turonski, Rik Yoshida

from whom I took material and adopted ideas...