Electron Ion Collider: An Overview

Hannah Bossi (Yale University) - ML Power Week - July 2023
Facilities at a glance

Large Hadron Collider
- Run 1
- LS1
- Run 2
- LS2
- Run 3
- LS3
- Run 4
- LS4
- Run 5
- LS5
- Run 6

STAR
- 2010
- 2020

PHENIX
- 2020
- 2030

sPHENIX
- 2030
- 2040

ePIC
- 2040

Electron Ion Collider

Relativistic Heavy Ion Collider
**EIC at a glance**

- **Electron Ion Collider (EIC)** is an electron-nucleus collider that will be built at Brookhaven National Laboratory (US).
- Construction starts in ~ 2024.
- Data-taking begins in ~ 2031.
- Budget: 2.1 billion €
- Already has active community including 251 member institutions from 33 countries

**This week we will contribute to this project!**
Collisions between electrons & protons/nuclei

Study structure of protons/nuclei by using the electron beam as a “microscope”

- Called deep inelastic scattering (DIS)
Kinematic variables of the EIC

\[ Q^2 = s \cdot x \cdot y \]

- "Resolution power" in the nucleus
- COM energy squared
- Fraction of nuclei’s momentum carried by parton
- Scattering inelasticity
Parton distribution functions

- Previous facility, HERA, collided protons with electrons/positrons to measure distribution of parton momentum fractions (aka parton distribution functions or PDFs)
- EIC will do something similar at lower energies, higher luminosities, and with a nuclear beam with hadron polarization.
- Why do we want to do this?
EIC goal #1: 3D imaging of nuclei

- Accelerated particles have an “ocean” of gluons and a “sea” of virtual quark-antiquark pairs
- Pairs can be formed by gluon interactions and annihilate to form gluons
- EIC will use high energy electron at a range of energies to take 3D “images” of protons and nuclei.
EIC goal #2: gluon saturation

- Growth in gluon pdf at low $x$ is due to gluon splitting
- When you squeeze many gluons in small nucleus, gluons will recombine
- Balance of splitting/recombination creates a state of *gluon saturation* called the *color glass condensate*

Want to observe this experimentally!
EIC goal #3: proton spin puzzle

- In proton, valence quarks (u,u,d) carry large fraction of the proton’s momentum (x) but a very small fraction of its spin.
  - Spin influences many other characteristics of the proton, but its precise origin remains unknown!
- EIC will have polarized electron and proton beams
  - Will enable precise studies of both quark and gluon contributions to spin!

Image credit: BNL
EIC goal #4: quarks, gluons, and confinement

- We know that distribution of quarks in a nucleus is different from that in a proton
  - Due to an effect called “nuclear shadowing”.
  - One goal of EIC is to test this also for gluons!
- Another main goal is to study the mechanism underlying the confinement of quarks and gluons into hadrons!
ML at the EIC

- The EIC is a futuristic detector being designed with future techniques in mind!
  - *ML/AI will play a large role!*
- Ongoing activities with AI
  - Detector design
  - Simulation
  - Reconstruction
  - Particle Identification
  - Analysis

See [AI4EIC workshop](#) for more information!
Computing at the EIC

<table>
<thead>
<tr>
<th>Stage</th>
<th>Input/Output</th>
<th>Reduction Factor</th>
<th>Technology options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compute Interface (e.g. FE-LIX)</td>
<td>100Tbps/10Tbps</td>
<td>$\times 10^{-1}$</td>
<td>FPGA</td>
</tr>
<tr>
<td>Online Event Filter</td>
<td>10Tbps/1Tbps</td>
<td>$\times 10^{-1}$</td>
<td>FPGA, (GPU), CPU</td>
</tr>
<tr>
<td>Online Buffer</td>
<td>1Tbps/0.5Tbps</td>
<td>$\times 5 \times 10^{-1}$</td>
<td>&lt; disk &gt;</td>
</tr>
<tr>
<td>Offline Event Filter</td>
<td>0.5Tbps/100Gbps</td>
<td>$\times 2 \times 10^{-1}$</td>
<td>FPGA, GPU, CPU</td>
</tr>
<tr>
<td>Reconstruction</td>
<td>100Gbps/10Gbps</td>
<td>$\times 10^{-1}$</td>
<td>(FPGA), GPU,CPU</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100Tbps/10Gbps</strong></td>
<td>$\times 10^{-4}$</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Data rates and reduction factors for proposed near real time data flow. Estimated data rate from ECCE detector is $O(100Tbps)$. Raw storage will be $O(100Gbps)$. Reconstructed object storage will be $O(10Gbps)$. Parentheses indicate technologies that could be used, but seem less likely choices.

<table>
<thead>
<tr>
<th>CPU Compute</th>
<th>year-1</th>
<th>year-2</th>
<th>year-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recon process time/core</td>
<td>5.4s/ev</td>
<td>5.4s/ev</td>
<td>5.4s/ev</td>
</tr>
<tr>
<td>Streaming-unpacked event size</td>
<td>33kB</td>
<td>33kB</td>
<td>33kB</td>
</tr>
<tr>
<td>Number of events produced</td>
<td>121 billion</td>
<td>605 billion</td>
<td>5,443 billion</td>
</tr>
<tr>
<td>CPU-core hours (recon-only, 1 pass)</td>
<td>181Mcore-hrs</td>
<td>907Mcore-hrs</td>
<td>8165Mcore-hrs</td>
</tr>
<tr>
<td>CPU-core hours (calib-only)</td>
<td>9Mcore-hrs</td>
<td>45Mcore-hrs</td>
<td>408Mcore-hrs</td>
</tr>
<tr>
<td>2020-cores needed to process in 30 weeks</td>
<td>38k</td>
<td>189k</td>
<td>1701k</td>
</tr>
</tbody>
</table>

Table 6: Estimates of CPU needed for reconstruction of raw data. The number of seconds per event is highly dependent on the type of processor being used. Number of events comes from total raw data storage estimate in table 4. Calibration is assumed to be 5% of reconstruction time.

** note these will definitely change - just a guess

[Scientific Computing Plan for EIC]
EIC Facility

- EIC will be an upgrade of the Relativistic Heavy-Ion Collider
- Use existing ion ring, add electron ring

**RHIC:** 2 ion accelerator/storage rings

**EIC:** One ion accelerator/storage ring, one electron accelerator ring, and one electron storage ring.
Machine parameters

- **Center of Mass Energy:** 20-140 GeV
- **Electrons:** 2.5 - 18 GeV
- **Protons:** 40 - 275 GeV
- **Luminosity:** $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- **Ion species:** $p \rightarrow U$ (variety of species already in use at RHIC)
- **Detectors:** Possible for two full coverage detectors
Interaction points

- Two possible detector locations
- Currently one detector (maybe 2nd to come)
  - **Electron-Proton/Ion Collider Experiment (ePIC)**
  - Collaboration formed since July 2022
ePIC detector

- Hermetic coverage for tracking, electromagnetic and hadronic calorimetry ($|\eta| < 4$)
- Proton/ion has much larger kinetic energy than electron, most hadrons emitted in hadron endcap

- We will focus on the precise forward calorimeters needed!
Barrel calorimeters at a glance

- **OHCAL/IHCAL**
  - Fe/scintillator sampling calorimeter
  - Reuse from sPHENIX
- **Barrel ECAL (review complete)**
  - Sci-Glass: homogenous, projective
  - Sci-Glass ECAL
  - Imaging: 6 layers of 0.5x0.5mm
  - Astro-Pix Silicon layers, interleaved with Pb-SciFi calorimeter
Forward calorimeter design needs

- Tracking momentum and angular resolution worsens above $\eta = 3$
  - Rely heavily on calorimeters for energy and spatial distribution of particles.
- Electromagnetic calorimeter
  - Measure the angle and energy of photons, identify electrons
- Hadronic Calorimeter
  - Measure charged hadrons, neutrons, $K^0_L$ with good resolution for low energy hadrons $E \sim 20$ GeV
Forward calorimeters

Longitudinally separated hadronic forward calorimeter (LFHCal)

Forward electromagnetic calorimeter (fEMC or pECal)
Forward electromagnetic calorimeter

- Highly granular W-scintillating fiber calorimeter
- fEMC → pECal
- Sits in front of the LFHCAL
Forward hadronic calorimeter

- Longitudinally separated forward hadronic calorimeter (LFHCal) - two sliding discs
- Fe-scintillator and W-scintillator sampling calorimeter
- Highly segmented w/ 7 long segments
- 3.58 m from IP

<table>
<thead>
<tr>
<th>parameter</th>
<th>LFHCal</th>
</tr>
</thead>
<tbody>
<tr>
<td>inner x, y</td>
<td>60 cm</td>
</tr>
<tr>
<td>outer radius (envelope)</td>
<td>270 cm</td>
</tr>
<tr>
<td>$\eta$ acceptance</td>
<td>$1.2 &lt; \eta &lt; 3.5$</td>
</tr>
<tr>
<td>tower information</td>
<td></td>
</tr>
<tr>
<td>x, y</td>
<td>5 cm</td>
</tr>
<tr>
<td>z (active depth)</td>
<td>130 cm</td>
</tr>
<tr>
<td>z read-out</td>
<td>10 cm</td>
</tr>
<tr>
<td># scintillator plates</td>
<td>65 (0.4 cm each)</td>
</tr>
<tr>
<td># absorber sheets</td>
<td>61 (1.52 cm steel)</td>
</tr>
<tr>
<td></td>
<td>4 (1.52 cm tungsten)</td>
</tr>
<tr>
<td>interaction lengths</td>
<td>$6.5 \lambda / \lambda_0$</td>
</tr>
<tr>
<td>Sampling fraction $f$</td>
<td>0.035</td>
</tr>
<tr>
<td># towers</td>
<td>8916</td>
</tr>
<tr>
<td># modules</td>
<td></td>
</tr>
<tr>
<td>8M</td>
<td>1077</td>
</tr>
<tr>
<td>4M</td>
<td>75</td>
</tr>
<tr>
<td># read-out channels</td>
<td>$7 \times 8916 = 62,414$</td>
</tr>
</tbody>
</table>

[LFHCal R&D Proposal, 2023]
Forward hadronic calorimeter

7 layers

4M Tower

8M Tower

16mm steel plates
4 mm scintillator tiles
HGCROC read-out board
transfer PCB
16mm tungsten plates

8M tower module - 20 cm x 10 cm x 140 cm
- 8.5 cm x 5 cm LFHCal towers

hadrons
Asymmetries around the beam pipe

- 2 discs with a radius of ~270 cm that will close in very closely around the beam pipe
  - Can be wheeled out in case beam quality is not good
- Region closest to the beam pipe has some asymmetries due to support structures

Can see this in the input data - this is not a bug
Other remarks on input data

- We have received some simulated calorimeter data for this week’s project
- This reflects the current “best” simulation - will likely change
  - Our feedback also matters - let us know what would be helpful to save!
- Resolution is better than what can be expected
  - Ex: perfect timing resolution (more realistic would be +/- 5% gaussian smearing)

Thanks to Friederike Bock and Nicolas Schmidt for providing us with the necessary info/simulations for this project!
Backup