Streaming Readout for sPHENIX and EIC

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Thanks to the inputs from many colleagues!
Also with reference to talks at Streaming Readout VIII and AI4EIC workshops
Relativistic Heavy Ion Collider

Φ 1.2km

Mar 2010
Highly polarized electron and nucleon beams, Ion beams from D-> U or Pb.

Hadrons up to 275 GeV, Electrons up to 18 GeV

√s = 20 GeV - 141 GeV, supporting two IPs

High luminosity $10^{34}$cm$^{-2}$s$^{-1}$ ($\geq 100x$ HERA luminosity)
Jet cor. & substructure
Vary momentum/angular size of probe

Parton energy loss
Vary mass/momentum of probe

Upsilon spectroscopy
Vary size of the probe

Cold QCD
Vary temperature of QCD matter
15 kHz calo trigger + 10% streaming DAQ
10 GB/s data logging
~1 years! From now to first data
sPHENIX magnet installation
RHIC IP8 Hall, Oct 7, 2021

13/32 sPHENIX hadronic calorimeter sectors installed
Related streaming readout electronics

**Associated test projects**
- Precision timing digitizer DRS4GIO (SBIR/LDRD)
- High density multiplexer+ ADC RFSoC Digitizer (LDRD)
- MVTX RU, 200M ch
- INTT ROC, 400k ch
- ALPIDE (ALICE/sPHENIX), FPHX (PHENIX)
- TPC FEE, 160k ch
- SAMPAv5 (ALICE/sPHENIX)

**sPHENIX streaming DAQ for tracker**
- FELIX
- Server
- COTS Network & Storage
- Exp. Hall
- Global Timing Module (NSLS II/sPHENIX) Receiving from RHIC RF low glitter clock source

48x 10-Gbps bi-directional optical links per FELIX

10/100 Gbps Network

**BNL-712 / FELIX v2 x38 (ATLAS/sPHENIX)**

**FELIX Ref:** 10.1109/tim.2019.2947972
Similar role as PICe40 in LHCb [R. Aaij’s talk]

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sPHENIX Streaming data flow

EIC Detector

- FEE, Buffer $\Delta t \sim \mu s$
- Digitizer
- ASIC/FPGA

DAQ room

- DAQ, Buffer $\Delta t \sim s$
- FELIX Interface
- Servers

Storage

- Disk $\rightarrow$ Tape

Online Buffer: 1.2PB x6

- Tape for perm. storage
- Fixed latency (2wk) offline reco.

Exp. Hall

- Trigger
- Timing

ADCs: $O(100)$Tbps
Expect 100% usage

$O(10k)x$ ASIC: zero suppression

Optical BW: 20Tbps
Expect 10% usage

38x FELIX Interface: trigger throttling, buffer

PCIe BW: 5Tbps
Expect 5% usage

38x Dual-EPYC7352 servers: compression, buffer

Network BW: 1.5Tbps
Expect 10% usage

Buffer: $\sim 7PB$
Few days of buffer

Analog

Digital

Clock/Sync, Slow control

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Streaming readout status at sPHENIX

- All three sPHENIX tracking detector uses streaming readout
- Developed plan to take streaming data for heavy flavor physics program (next slides), commended by RHIC PAC.
- Completed construction of sPHENIX FELIX DAQ interface (~50) and procurement of DAQ servers, network infrastructure and online disk buffers
- Data taking start in 2023!

RHIC PAC 2020 report

We commend sPHENIX for developing the continuous streaming readout option for the detector, which increases the amount of data that can be collected in Run-24 by orders of magnitude. In particular in the sector of open heavy flavor, this technique will give access to a set of qualitatively novel measurements that would otherwise not be accessible. Given the tight timeline for completing the RHIC physics program before construction of the EIC begins, this is a tremendous and highly welcome achievement.
TPC data stream in sPHENIX triggered DAQ

What detector sends out:
Continues readout data stream

What we write to disk:
20% data @ O(100) Gbps
Each seg. corresponding to a calorimeter trigger
SRO-Mode1-Simple [Recommended]

Simply prolong L1-Acceptance signal to each subsystem, from 1 BCO to $T_{SRO} \sim 67$ beam crossings ($\sim 7$us or 10% SRO data)
→ x500 increase of hard-to-trigger p+p sample
→ at cost only 50% increase in data vol. (by piggy back on long TPC readout window of 13us)

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**Beam counter**
Latency: 0 BCO

**Recorded Collisions**

**vGTM TPC Acceptance**
Latency: $T_{L1} \sim 40$ BCO

**TPC Data Output**
Latency: $> T_{L1}$

**vGTM INTT Acceptance**
Latency: $T_{L1}$

**INTT Data Output**
Latency: $> T_{L1}$

**MVTX Strobe Window**
Latency: 0 BCO

**vGTM MVTX Acceptance**
Latency: $T_{L1}$

**MVTX Data Output**
Latency: $> T_{L1}$

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Streaming-DAQ enabled scientific connection:
e.g. gluon dynamics via heavy flavor $A_N$

sPHENIX $D^0$ trans. spin asymmetry, $A_N \rightarrow$ Gluon Sievers via tri-$g$ cor.

Universality test on gluon Sievers

EIC SIDIS $D^0$ transverse spin asymmetry $\rightarrow$ Gluon Sievers

$sPHENIX$ Projection, $p^+p \rightarrow D^0/D^0 +X$, $P=0.57$

- 6.2 $pb^{-1}$ str. $p+p$, Years 1-3 $\leftarrow$ 10% Streaming DAQ
- 86 $pb^{-1}$ str. $p+p$, Years 1-5 $\leftarrow$ 100% Streaming DAQ

Kang, PRD78, $\lambda_t = \lambda_d = 0$

Kang, PRD78, $\lambda_t = -\lambda_d = 70$ MeV

$e+p \rightarrow D + \overline{D} + X$

Projected Luminosity 100 fb$^{-1}$

Det. Matrix PID

$Q^2 > 1$ GeV$^2$

$e+p^+ \rightarrow D + \overline{D} + X$

[CNFS HF@EIC workshop, Nov 4-6, 2020]
EIC experiments

Generic EIC Detector model [EIC YR]

See also: proposal detectors in development

- ATHENA: athena-eic.org
- CORE: eic.jlab.org/core
- ECCE: ecce-eic.org
EIC: unique collider
→ unique real-time system challenges

<table>
<thead>
<tr>
<th></th>
<th>EIC</th>
<th>RHIC</th>
<th>LHC → HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision species</td>
<td>$\bar{e} + \bar{p}, \bar{e} + A$</td>
<td>$\bar{p} + \bar{p}/A, A + A$</td>
<td>$p + p/A, A + A$</td>
</tr>
<tr>
<td>Top x-N C.M. energy</td>
<td>140 GeV</td>
<td>510 GeV</td>
<td>13 TeV</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>10 ns</td>
<td>100 ns</td>
<td>25 ns</td>
</tr>
<tr>
<td>Peak x-N luminosity</td>
<td>$10^{34}$ cm$^{-2}$ s$^{-1}$</td>
<td>$10^{32}$ cm$^{-2}$ s$^{-1}$</td>
<td>$10^{34} \rightarrow 10^{35}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>x-N cross section</td>
<td>50 μb</td>
<td>40 mb</td>
<td>80 mb</td>
</tr>
<tr>
<td>Top collision rate</td>
<td>500 kHz</td>
<td>10 MHz</td>
<td>1-6 GHz</td>
</tr>
<tr>
<td>dN$_{ch}$/dη in p+p/e+p</td>
<td>0.1-Few</td>
<td>~3</td>
<td>~6</td>
</tr>
<tr>
<td>Charged particle rate</td>
<td>4M $N_{ch}$/s</td>
<td>60M $N_{ch}$/s</td>
<td>30G+ $N_{ch}$/s</td>
</tr>
</tbody>
</table>

- EIC luminosity is high, but collision cross section is small ($\propto \alpha_{EM}^2$) → low collision rate
- But events are precious and have diverse topology → hard to trigger on all process
- Background and systematic control is crucial → avoiding a trigger bias
EIC DAQ in Fun4All-EIC simulation


Beam gas event
p + p(gas), 275 GeV/c at z=-4 m

e+p DIS 18+275 GeV/c
Q^2 \sim 100 (\text{GeV/c})^2
Data Rate

MAPS silicon tracker
Raw data: 16-24 bit / MAPS hit (3-layer ALPIDE model)

TPC
Raw data: 3x5 10 bit / TPC hit + headers (60 bits)

Forward/backward GEM
Raw data: 3x5 10 bit / GEM hit + headers (60 bits)

e+p, Pythia6 Q2>0

p+p(gas) Pythia8

Very long tails to 1000 hits at P=10^-6

**Signal data rate -> DAQ strategy**

- **What we want to record:** total collision signal $\sim 100 \text{ Gbps} @ 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
  - Assumption: sPHENIX data format, 100% noise, Less than sPHENIX peak disk rate. $10^{-4}$ comparing to LHC collision

- **Therefore, we could choose to stream out all EIC collisions data**
  - In addition, DAQ may need to filter out excessive beam background and electronics noise, if they become dominant.
  - Very different from LHC, where it is necessary to filter out uninteresting p+p collisions (CMS/ATLAS/LHCb) or highly compress collision data (ALICE)

![EIC-sPHENIX simulation](image)

- E$+p$, $\sqrt{s} = 140$ GeV, $L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Signal rate for tracker + calorimeter = 40 Gbps

- p + p(beam gas), 250 GeV/c, |z|<450 cm
- $I(p) = 1A$, $V_{ac} = 10^{-9} \text{ mbar}$, Gas event @ 12 kHz
- Beam gas bkg rate for tracker + calorimeter = 1 Gbps

Refs: EIC CDR, sPH-cQCD-2018-001

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Strategy for an EIC real-time system

- **EIC streaming DAQ**
  - Triggerless readout front-end (buffer length : μs)
  - DAQ interface to commodity computing (e.g. FELIX/CRU). Background filter if excessive background rate
  - Disk/tape storage of streaming time-framed zero-suppressed raw data (buffer length : s)
  - Online monitoring and calibration (latency : minutes)
  - Final Collision event tagging in offline production (latency : days+)

Ref: EIC-CDR
**Blurred boundary with offline computing**

See also: last talk M. Battaglieri

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**Detector**
- FEB (digitization)
- FELIX-like
- Offline Event Filter (CPU, FPGA, GPU)

**Online Buffer**
- EBDC (few days)
- Online Event Filter

**Offline Event Filter?**
- Calibrate
- Offline Buffer (few weeks)

**Reconstruction**
- Raw storage

**Data Center(s): SDCC, JLab, …**
- (Operations Funds)

**Experimental Hall and Counting House (Project Funds)**

**HTC Compute Facilities**
- SDCC, JLab, … (Operations)

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*Courtesy: David Lawrence*  
*ECCE computing model [link]*
Despite low signal rate, the raw data rate can be filled with noises and background
  ◦ Need low background & low noise detector & electronics design

An essential job of EIC real-time computing: reliable streaming data reduction to fit permanent storage (next topics)

And more traditional roles for online/offline server farm:
  ◦ Online monitoring/fault det.
  ◦ Calibration
  ◦ Production → Initial analysis pass
Online computing for streaming data – trigger throttling

- At the beginning of the EIC operation, background & noise rate could be unpredictable and high

- A contingency method: throttling streaming data with triggering
  - Immediately reduce streaming data by orders of magnitudes
  - Widely used hardware producing trigger, fix latency or HLT (Aaji’s talk)
  - Has physics loss, added systematic uncertainty for hardware trigger efficiency

- Can utilize ML to produce more complex triggering on FPGA
  - PID trigger, e.g. ref: S. Furletov @ streaming workshop VIII [link]
  - Tracking-event topology trigger: D. Yu @ AI4EIC workshop [link]
Online computing for streaming data - compression

- Lossless compression
  - Compress by ~1/2
  - Well established fast compression algorithm

- Lossy compression
  - Opportunity for unsupervised machine learning based on data, e.g.
  - Auto-encoder on ASIC for HGCal @ CMS [link]
  - Bicephalous Convolutional Neural Encoder for zero-suppressed data (next)
Bicephalous Convolutional Auto-Encoder for zero-suppressed data

- Some detector ADC data is challenging for Auto-Encoder, e.g. features such as zero-suppression cut off
- A dual-output auto encoder is designed to output both a region of interest and decompressed ADC. Possibility for further noise filtering
- Ref: Y. Huang @ AI4EIC workshop [link]

Compression comparison with published compressor tested on busiest sPHENIX TPC timeframes
Another effective way of suppressing background is feature building, e.g.

- Clustering on calorimeter
  - Effective in suppressing single tower noise
  - e.g. CLAS12 test as in M. Battaglieri’s talk

- Tracklet building on tracker:
  - Effective in suppressing isolated noise, such as the synchrotron background
  - e.g. ALICE TPC streaming data [arXiv:1910.12214]. D. Yu @ AI4EIC workshop [link]

- ADC timeseries -> amplitude extraction
  - e.g. Specialized filters: C. Crawford @ Streaming readout VIII [link];
  - Neural network on ASIC: S. Miryala @ Streaming readout VIII [link]
Summary

- sPHENIX under construction for start of data taking in 2023
  - Recent development on streaming data (on top of streaming readout) for sPHENIX tracker show significant increase of physics capability
  - Strong link with EIC both technical implementation and physics program
- EIC is a unique collider with low x-section, high luminosity and stringent requirement on systematic control.
  - Streaming readout fit well, wide adoption in community [YR, CDR]
  - EIC collision signal data rate is low, but noise/background rate uncertain
  - EIC online computing: key development on reliable noise/background filtering
Questions?
Extra information
EIC x-sec : further quantification [Courtesy E. Aschenauer]

- Inelastic e+p scattering x-sec:
  - For a luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$, 50 ub corresponds to 500 kHz

- Elastic e+p cross-section:
  - For EIC central barrel, elastic cross section is small comparing to the inclusive QCD processes

- Beam gas interaction:
  - Beam proton – beam gas fix target inelastic interactions. The pp elastic cross section is smaller (~7 mb)
  - For a vacuum of $10^{-9}$ mbar in the detector volume (10m) this gives a rate of 14 kHz

<table>
<thead>
<tr>
<th>Beam [GeV]</th>
<th>HERA</th>
<th>5 x 50</th>
<th>10 x 100</th>
<th>18 x 275</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q^2 &gt; 10^{-9}$ GeV</td>
<td></td>
<td>65.6</td>
<td>29.9</td>
<td>41.4</td>
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<tr>
<td>$Q^2 &gt; 1$ GeV</td>
<td></td>
<td>1.29</td>
<td>0.45</td>
<td>0.65</td>
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<tbody>
<tr>
<td>$\sigma [\gamma_{Exp} &gt; -4]$</td>
<td>5 pb</td>
<td>5 ub</td>
<td>0.7 ub</td>
<td>0.06 ub</td>
</tr>
<tr>
<td>$\sigma [\gamma_{Exp} &gt; -6]$</td>
<td>11 ub</td>
<td>420 ub</td>
<td>100 ub</td>
<td>29 ub</td>
</tr>
</tbody>
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<tr>
<th>$E_p$</th>
<th>50 GeV</th>
<th>100 GeV</th>
<th>275 GeV</th>
<th>920 GeV</th>
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<tbody>
<tr>
<td>$\sigma$</td>
<td>38.4 mb</td>
<td>38.4 mb</td>
<td>39.4 mb</td>
<td>41.8 mb</td>
</tr>
</tbody>
</table>
**Results I: AE v.s. Bicephalous AE**

Compression ratio is 1 : 27

(1 : 3 for SAMPA ASIC for this busiest event)
Result III. Ablation Study