The Readout and Data Acquisition Design of the sPHENIX Detector at RHIC

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RHIC from space

Manhattan

Long Island, NY

RHIC from space
Quite a number of different detectors
4 Arms and central detectors
No hermetic coverage
PHENIX -> sPHENIX

PHENIX has been around since the early 90’s
Started taking data in 2000, first Physics Run in 2001 – Run 16 is ongoing
400+ people collaboration, 200-ish publications, some “famous” ones among them
Still, the experiment is showing its age – much older than the cars most of us drive
The missing hermetic coverage is an issue for today’s analyses
Limitations of the 90’s designs look strange to us today
A wealth of new insights guides us what to look for next, how to build the next-gen detector
RHIC and (s)PHENIX

The Relativistic Heavy Ion Collider
Huge variety of ions possible - Au, Cu, $^3$He, $^{238}$U so far, but pretty much anything is possible
Polarized protons – a unique facility
500GeV/proton -> 200GeV/N for Au
Dedicated HI and polarized proton facility

PHENIX – high-rate heavy-ion experiment
Electromagnetic probes - Photons, electrons, muons
Heavy quarks & quarkonia
sPHENIX from a Physics Perspective… Jets!

- The days of measuring single particles, in however a comprehensive way, are largely over.
- Most analyses look for some form of correlations between particles in individual events.
- Reaction planes, the now-famous long-range correlation “ridge”, jets.
- Jets in particular is what carries the physics these days – probing the medium.
Jets

Jets are made in hard QCD scattering of quarks or gluons. You get an initial pair of quarks with (mostly) opposite momentum. Quarks hadronize – they produce a “spray” of particles in narrow cone, the “jets.” So we are looking for those back-to-back cones of particles.
So, what do we want?

While we have a number of jet measurements, the PHENIX acceptance is too small (and has too many holes) to be a good jet detector

So what we want is:

• full azimuthal coverage, large coverage in rapidity (+- one unit)
• decent tracking
• electromagnetic and hadronic calorimetry
• compact

So let’s go and upgrade the experiment!
Why didn’t we build PHENIX like that in the first place?

The available materials at the time were such that a full-azimuth detector would not fit into the experimental hall. Only new techniques and materials make this possible, 20+ years later.

“Lake PHENIX” level

If one digs just a few inches, there’s water…
sPHENIX – the Concept

- Outer HCAL \(\approx 3.5\lambda_i\)
- Magnet \(\approx 1.4X_0\)
- Inner HCAL \(\approx 1\lambda_i\)
- EMCAL \(\approx 18X_0 \approx 1\lambda_i\)
- Tracker

HCAL steel and scintillating tiles with wavelength shifting fiber
- 2 longitudinal segments.
- An Inner HCal inside the solenoid.
- An Outer HCal outside the solenoid.
- \(\Delta \eta \times \Delta \phi \approx 0.1 \times 0.1\)
- 2 x 24 x 64 readout channels
- \(\sigma_E/E < 100\%/\sqrt{E}\) (single particle)

SiPM Readout
The EmCal (this is really the special item...)

A lot of the space savings (compared to PHENIX) are found in the Emcal
In the 90’s, the standard EmCal was Lead Scintillator or Lead glass
Comparable radiation lengths and Moliere radii for both – **28mm and 37mm**
Metallic tungsten would be cool, \( X_0 = 3.5\text{mm} \)!
But impossible to machine, melt, form...
Then a solution came from the most unlikely place – a golf club manufacturer
Instead of using metallic tungsten, use a paste of tungsten powder and epoxy
Not as dense as pure tungsten, but good enough – \( X_0 \approx 7\text{mm} \)
Can be shaped in any form (e.g. golf club heads), is cheap (uses “scrap” tungsten)
So we build the EmCal out of that!
Tungsten Powder EmCal Modules

We are producing Emcal modules in-house (UIUC), and at a company called THP

Avg density $\sim 9.3 \text{ g/cm}^3 \pm \sim 0.1 \text{ g/cm}^3$

Heavier than solid Lead

The mold with scintillating fibers

All calorimeters are read out with SiPMs
Talking about the Readout of all that…

PHENIX has never been afraid of high data rates and volumes
I personally claim a portion of that fame…
We fully intend not to sacrifice data and “take all we can”
Current design goal is 15KHz of event rate
This is possible right now, but will be less of an issue in 2020+

sPHENIX will have an estimated 15-25 GByte/s fully compressed data stream
The sPHENIX DAQ

- As much as possible, we will re-use the existing PHENIX DAQ
- We have been asked by review committee members why we wouldn’t want to upgrade a 15yr old DAQ
- Answer: We already did that, we have just the system that we would build today
- At least for the front-end!
- Legacy gear from older detectors goes out the window
- Working and very modern front-end, lots of experience
- We have traditionally taken the highest data rates in the field
- 15KHz event rate envisioned, 14 have been demonstrated
- Most of the work is in the back-end, event builder, etc
- Test beam setup used an improved DAQ system already
Much less variety

• PHENIX had 14 different detector system, each with its assorted front-end electronics
• Herculean integration efforts early on
• sPHENIX, by conscious design, has only a few and common technologies
• Concentrate on uptime
DAQ Overview

- **DCM-2** receives data from digitizer, zero-suppresses and packages
- **SEB** collects data from a DCM group (~35)
- **ATP** Assembles events and compresses data (~60)
- **Buffer Box** data interim storage before sending to the computing center (7)

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**Interaction Region**

**Rack Room**

**Event Builder**

**To HPSS**

**Computing Facility**

15
Slot Controllers

- Provide monitoring and control for EmCal and HCal Interfaces.
- Temperature and leakage stabilizer functions.
- Temperature gain correction critical for SiPMs
- Near-production boards used for EmCal and Hcal during beam test.
Digitizer/ADC Boards, XMIT, Controller

- Goal is to run the next test beam (January 2017) with new digitizer electronics
- 64 channels per board
- 14 bit ADC
- 60 MHz sampling frequency
- XMIT board interfaces 4 ADC boards to DCM-II
- Controller board interfaces to SEB
DAQ Components – DCM2

• The Data Collection Module V2 is a modern, mature board commissioned in PHENIX Runs 14,15
• “just as we would have built it” for sPHENIX
• FPGA code, tools, existing configurations to draw from
• Configuration tools / description language in place
• O(200) units
• Production-grade boards in hand for test beams, R&D, etc as soon as the PHENIX Run ends (end of June)
FNAL Testbeam Impressions

- Need to verify our simulation results with test beams before production
- Had a really good run with few problems
- Unified data taking for all (or at least most) projects with RCDAQ
- Rcdaq is in use in sPHENIX and the EIC orbit (BNL, UIUC, SBU, Yale, GSU, even ATLAS ZDC test beam/calibration)
- Produces the eventual sPHENIX data format (PRDF)
- Ideal to get students to be proficient working with the raw data
Metadata Logging

Martin says: “Log everything you can think of. And then log some more.”

• Log automatically. Do not rely on human input. How was the DAQ configured? What was the HV? Were the lights on? What was the ambient temperature? Was something upstream in the beamline?
• Many things just for “forensics” purposes in case something doesn’t make sense
• I truly believe in taking pictures – a pic captures everything
• Metadata captured in a database, but also in the raw data
• Info cannot get lost, easy to access if you have the raw data file
We had a RPi that was aware of the spill end – we fed it a copy of the spill signal into a high-tech board

### Energy
- S:MTNRG = -16 GeV
- F:MT6SC1 = 10129 Cnts
- F:MT6SC2 = 9013 Cnts
- F:MT6SC3 = 7829 Cnts
- F:MT6SC4 = 0 Cnts
- F:MT6SC5 = 158725 Cnts

### Beamline Counters
- E:2CH = 248.3 mm
- E:2CV = 11.33 mm
- E:2CMT6T = 73.44 F
- E:2CMT6H = 39.7 %Hum
- F:MT5CP2 = 1.242 Psia
- F:MT6CP2 = 1.492 Psia
“It appears that the distributions change for Cherenkov1 at 1,8,12, and 16 GeV compared to the other energies. It seems that the pressure is changed. [...] Any help on understanding this would be appreciated.”
Martin: “Look at the info in the data files”:

<table>
<thead>
<tr>
<th>Command</th>
<th>Data File Name</th>
<th>Data Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ ddump -t 9 -p 910 beam_00002298-0000.prdf</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S:MTNRG = -1 GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F:MT6SC1 = 5790 Cnts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F:MT6SC2 = 3533 Cnts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F:MT6SC3 = 1780 Cnts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F:MT6SC4 = 0 Cnts</td>
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<tr>
<td>F:MT6SC5 = 73316 Cnts</td>
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<tr>
<td>E:2CH = 1058 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E:2CV = 133.1 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E:2CMT6T = 73.84 F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E:2CMT6H = 32.86 %Hum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F:MT5CP2 = .4589 Psia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F:MT6CP2 = .6794 Psia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$ ddump -t 9 -p 910 beam_00002268-0000.prdf</td>
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<td></td>
</tr>
<tr>
<td>S:MTNRG = -2 GeV</td>
<td></td>
<td></td>
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<tr>
<td>F:MT6SC1 = 11846 Cnts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F:MT6SC2 = 7069 Cnts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F:MT6SC3 = 3883 Cnts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F:MT6SC4 = 0 Cnts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F:MT6SC5 = 283048 Cnts</td>
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<td>E:2CH = 1058 mm</td>
<td></td>
<td></td>
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<tr>
<td>E:2CV = 133 mm</td>
<td></td>
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</tr>
<tr>
<td>E:2CMT6T = 74.13 F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E:2CMT6H = 37.26 %Hum</td>
<td></td>
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<tr>
<td>F:MT5CP2 = 12.95 Psia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F:MT6CP2 = 14.03 Psia</td>
<td></td>
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</tbody>
</table>
More Forensics

“Was the scintillator test contraption in the beam in run 2743? There is a higher fraction of showering than before.”

Look at the cam pictures we automatically captured for each run:

```
$ ddump -t 9 -p 940 beam_00002742-0000.prdf > 2742.jpg
$ ddump -t 9 -p 940 beam_00002743-0000.prdf > 2743.jpg
```
Example: Temperature compensation

The FTBF A/C was hard at work – temperature cycles at the 30 mins level
Estimated -3.6%/°C gain variation in the SiPMs
Need to see the effect of offline temperature change compensation
Flashing just one test beam result

EMCAL Energy Resolution and Linearity

**Electron Resolution**
- T-1044, MIP calib.: $\Delta E/E = 5.4\% \pm 14.2\%/\sqrt{E}$
- T-1044, e-shower calib.: $\Delta E/E = 3.2\% \pm 12.7\%/\sqrt{E}$
- Simulation: $\Delta E/E = 2.4\% \pm 11.8\%/\sqrt{E}$

**Electron Linearity**
- T-1044 data
- Unity

*Preliminary!*
Summary

- sPHENIX will re-use the really modern parts of the PHENIX DAQ
- A workhorse “lean” DAQ system in hand to get us through all R&D
- Uses the actual sPHENIX electronics but can also read out standard devices, CAEN, the SRS, DRS4, etc
- Rich set of metadata logging features (“anything your computer knows”) for lab setups, test beams, R&D in general
- Test bed for new electronics to come
- SiPM automated temperature compensation in progress
- SPHENIX envisioned to see first beam in 2022
Taking a hint from Ikea

sPHENIX Monteringsföljd

1. **Första HCal-modulinstallationen**
   - Lyftande svängtapp
   - Första modulen shimsad, undersökt och injusterad

2. Fastsatt med nästa modul
   - Bultad till ändplattorna

3. Yttre HCal fungerar som stödstruktur för detektorn
   - Retur av magnetiskt flöde

4. Byggnadsställningar

5. Kartläggning av magnetflöden innan inre HCal-installationen

6. I-balkstöd

7. Linjärskenor
   - Stödring
   - Inre HCal-modul monteringsfixtur
   - Kort I-balk

8. Detektorinstallation
   - Vagn

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11/9/2015
Decommissioning, Installation and Integration
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DAQ Components – jSEB2 and SEB

A “Sub-Event Buffer” refers to a Linux PC with a “jSEB2” interface card. Card receives data from the DCM2’s via another board. First time data are seen in a standard PC. jSEB2 is a 4-lane PCI-Express card, 500MByte/s-capable. Code, tools, experience from Runs 14 & 15. Production-grade cards in hand. SEB is basis for test beam, R&D-type, small DAQs.
Data compression

After all data reduction techniques (zero-suppression, bit-packing, etc) are applied, you typically find that your raw data are still gzip-compressible to a significant amount.

Introduced a compressed raw data format that supports a late-stage compression.

![Diagram of data compression process]

- Buffer
- LZO algorithm
- Add new buffer hdr
- This is what a file then looks like
- LZO Unpack
- Original uncompressed buffer restored

All this is handled completely in the I/O layer, the higher-level routines just receive a buffer as before.
This compression buys you a lot of spare bandwidth and nice features (e.g., your analysis runs faster!)

However:

A late-stage compression (think: in your tape drive in the extreme case) doesn’t really help you.

The compression has to kick in before the data hit your storage system for the first time.

No single machine can keep up with compressing a >2GByte/s rate.
Switch to distributed compression

The Event builder has to cope with the uncompressed data flow, e.g. 1200MB/s ... 2500MB/s

The compression is handled in the “Assembly and Trigger Processors” (ATP’s) and can so be distributed over many CPU’s -- that was the breakthrough

The buffer boxes and storage system see the compressed data stream, 700MB/s ... 1300MB/s

Current compression levels: 100G become ~55G
Data Rates (Run14)
Trigger Electronics & Timing system

Trigger interface

Legend:
- MTM: Master Timing Module
- GTM: Granule Timing Module
- FEM: Front End Module
- GL1: Global Level 1 Trigger

Copper
Fiber

Front-end modules aka “Digitizers”
Local-Level 1 (LL1) Boards

• LL1’s generate a trigger signal from trigger primitives generated in the front-end for a given detector
• new LL1 boards for calorimeter triggers
• Potential new triggers for p+p, p+A need LL1 boards.
Trigger & Timing system

Detector

Analog Front End

Digital Front End

Trigger

GL1

L1 Busy

GTM

MTM

RHIC Clock

Clock/Trigger/Mode Bits

Event Builder

Monitoring

HPSS

Counting House
Some envisioned performance plots

The yield of hard processes in a typical RHIC year (22 weeks of running)

The lowest count in the plot corresponds to 10 billion events

(We expect to get 20)
Statistical reach for some probes

The way PHENIX gets to high PT is through \( \pi^0 \)s

That reaches to \(~20\text{GeV/c}\)

In sPHENIX, we can get to 4x that with jets
Upsilon states are observed with a resolution just shy of 100 MeV/c, enough to resolve the Upsilon states.
Tracking – 2 options, still very much under discussion

**All Si Tracker option**

**Si tracker**

- 7 layers strips and pixels
- Achieves design goals of pattern recognition and 100 MeV mass resolution on Upsilon states
- Total thickness ≈0.1X₀

**2 Pixel Layers + Compact TPC option**

**TPC + inner Si layers**

- 80 cm outer radius TPC
- Inner Si detector
- TPC electronics following from ALICE upgrade
The BaBar Magnet

We had looked at magnets, but none of the available ones were quite right, then --

The BaBar magnet secured from SLAC after SuperB canceled, arrived at BNL in February 2015

Considerable additional equipment also acquired (power supplies, dump resistor, quench protection, cryogenic equipment)

SMD and CAD preparing it for low power cold test

Well suited to our needs without compromises

1.5 T central field
2.8 m diameter bore
3.8 m long
1.4$X_0$ coil+cryostat

This really gave a tremendous boost to this project!
EmCal Modules

Tungsten-scintillating fiber SPACAL

Radiation length of ≈7 mm allows it to be inside the solenoid where only the material of the tracker is in front of it

Beam tested by UCLA group

Development of projective geometry which could improve e/π separation needed for the Upsilon measurements

Readout on inner radius of EMCAL with 4 3x3 mm SiPM’s

On-detector electronics limited to preamps, bias control and temperature monitoring
Projective Geometry

We want to make the EmCal projective, this is, each eta ring “looks” straight at the collision point. Superior over a “pineapple slice” design, angle of incidence is limited. That requires double-tapered modules to do it right. It is an engineering challenge though.
Density Uniformity, Sampling Fraction

The tapered design makes the sampling fraction change over the depth of the module – we need to test the energy reconstruction carefully.

The production process is not “industrial-grade” yet, still at the level of prototypes.

Still a good amount of density variation module by module – we are still learning the production process.

The latest batch of modules from Illinois
sPHENIX – step by step
32 sectors - 1.16m inner radius, 1.37m outer radius
10 rows of 7mm scintillator tiles (24 tiles per row)
32° tilt angle, tapered stainless steel plates
~10.2mm - ~14.7mm
Completed sector is 4.3m long, weighs ~ 1 ton
Outer HCal

32 sectors - 1.9m inner radius, 2.6m outer radius

10 rows of 7mm scint. tiles (24 tiles per row), 12° tilt angle

Tapered 1006 steel plates ~26.1mm - ~42.4mm

6.3 m long, 13.5 tons

Just because of the weight, the outer HCal tends to dominate our engineering discussions!

Scintillator tile

The drawing looks at the Hcal from "the back"
What we stick into the Test Beams…

A “sector” of the HCals, plus a small EmCal portion
Multi-Event buffering

• This is what makes the DAQ as fast as it is

• Or, in other words: that keeps the dead time in the low 90%’s

• Comes down to dealing with your data from various events in parallel
An another-world example

A Volkswagen assembly line

A given car takes about 28 hours from starting as a naked chassis to being an assembled vehicle.

One station adds the “skin”, another the engine, another installs the defeat devices – about 340 “stations”

Single-Event buffering – next car enters the assembly line once the previous car is done → one car every 28 hours

Multi-Event Buffering – car moves forward as soon as the next station is free → one car about every 5 minutes
Multi-Event buffering effect in the DAQ

![Graph showing DAQ livetime vs. rate with different runs indicated.]

- **single-event buffered runs**
Multi-Event buffering effect in the DAQ

In a rare-event experiment, you do not want to go down this path single-event buffered runs.
Multi-Event buffering effect in the DAQ

DAQ Livetime vs. Rate

Plus multi-event buffered runs

- Run2 Au+Au
- Run3 d+Au
- Run4 Au+Au
- Run5 Cu+Cu
- Run7 Au+Au