Update on PRad GEMs, Readout Electronics & DAQ

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Outline

- PRad GEMs update
- Upgrade of SRS electronics
- Integration into JLab DAQ system
- Cosmic tests in EEL
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The Proton Charge Radius Puzzle

Methods for measuring proton charge radius

- Electron-proton elastic scattering to determine electric form factor (Nuclear Physics)
  \[ \sqrt{<r^2>} = \sqrt{-6 \frac{dF(q)}{dq^2}} \bigg|_{q^2=0} \]

- Spectroscopy (Atomic physics)
  - Hydrogen Lamb shift
  - Muonic Hydrogen Lamb shift

- 7σ discrepancy between the atomic hydrogen Lamb shift and muonic hydrogen Lamb shift

- New Experiments:
  - Atomic spectroscopy
  - Muon spectroscopy (PSI)
  - Muon – proton scattering (MUSE, PSI)
  - Electron - Proton scattering with different schematics (JLab, Mainz)
The PRad Experiment @ JLab: $e^+e^- \rightarrow e^+e^-$ Scattering

### The Proton Charge Radius from $e^+e^- \rightarrow e^+e^-$ Scattering Experiments

- In the limit of first Born approximation the elastic $e^+e^-$ scattering (one photon exchange):
  \[
  \frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \left( \frac{E'}{E} \right) \frac{1}{1 + \tau} \left( G_E^2(Q^2) + \frac{2}{\pi} G_M^2(Q^2) \right) \]
  \[
  Q^2 = 4EE' \sin^2 \frac{\theta}{2} \quad \tau = \frac{Q^2}{4M_p^2} \quad \epsilon = \left[ 1 + 2(1 + \tau) \tan^2 \frac{\theta}{2} \right]^{-1}
  \]

- Structure less proton:
  \[
  \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} = \frac{\alpha^2}{4\pi^2} \left[ 1 - \beta^2 \sin^2 \frac{\theta}{2} \right]
  \]

- $G_E$ and $G_M$ were extracted using Rosenbluth separation (or at extremely low $Q^2$ the $G_M$ can be ignored, like in the PRad experiment).

- The Taylor expansion at low $Q^2$:
  \[
  G_E^2(Q^2) = 1 - \frac{Q^2}{6} \langle r^2 \rangle + \frac{Q^4}{120} \langle r^4 \rangle + \ldots
  \]

#### Specifications for PRad Experiment

- Non Magnetic spectrometer
- High resolution and high acceptance calorimeter $\Leftrightarrow$ low scattering angle $[0.7^\circ - 3.8^\circ]$  
- Simultaneous detection of $e^+e^- \rightarrow e^+e^-$ (Moller Scattering) $\Leftrightarrow$ minimize systematics
- High density windowless $H_2$ gas target $\Leftrightarrow$ minimize background
- clean CEBAF electron beam ($1.1$ GeV and $2.2$ GeV) $\Leftrightarrow$ minimize background

#### PRad Experiment (E12-11-106):

- High “A” rating (JLab PAC 39, June 2011)
- Experimental goals:
  - Very low $Q^2$ ($2 \times 10^{-4}$ to $4 \times 10^{-2}$)
  - 10 times lower than current data @ Mainz
  - Sub-percent precision in $\langle r_p^2 \rangle$ extraction
The PRad Experimental Setup in Hall B

**Target specs:**
- cell length 4.0 cm
- cell diameter 8.0 mm
- cell material 30 μm Kapton
- input gas temp. 25 K
- target thickness $1 \times 10^{18}$ H/cm²
- average density $2.5 \times 10^{17}$ H/cm³
- Cell pressure 0.6 torr
- Vacuum in target chamber ~$5 \times 10^{-3}$ torr

**HyCal specs:**
- 34 x 34 matrix of 2.05 x 2.05 x 18 cm³ PbWO₄ shower detectors
- 576 Pb-glass shower detectors (3.82x3.82x45.0 cm³)
- 5.5 m from $H_2$ target (~0.5 sr acceptance)
- Resolutions for PbWO₄ shower: $\sigma/E = 2.6 \%/\sqrt{E}$, $\sigma_{xy} = 2.5 \text{ mm}/\sqrt{E}$
- Resolution for Pb-glass shower detectors factor of ~2.5 worse

**GEMs:**
- factor of >10 improvements in coordinate resolutions
- similar improvements in Q2 resolution (very important)
- unbiased coordinate reconstruction (including transition region)
- increase Q2 range by including Pb-glass part
PRad GEMs: Assembly and cosmic tests @ UVa

- Both chambers were completed in February
- Cosmic test performed on check all sectors active
- Basic characterization of the performances are evaluated
PRad GEMs @ JLab

Mounted on aluminum support frames

Trigger scint. Power Supply

SRS crate

cosmic setup
Outline

✓ PRad GEMs update
✓ Upgrade of SRS electronics
✓ Integration into JLab DAQ system
✓ Cosmic tests in EEL
Multichannel electronics developed by the RD51 Collaboration for Micro Pattern Gaseous Detectors such as GEMs. It is based on:

- **SRS-APV25**: Front End cards (hybrids hosting the APV25 chip) mounted on the detector ➞ send multiplexed data from 128 channels to SRS-ADC cards via standard commercial HDMI cables.
- **SRS-ADC**: card that host the ADC chips, de-multiplex and convert data from up to 16 SRS-APV25 cards into digital format then send them to the SRS-FEC cards.
- **SRS-FEC**: is the FPGA board, handles the clock and trigger synchronization of the SRS-APV hybrid cards, send digitized data from ADC to the SRS-SRU via 1 Gb Ethernet Copper link.
- **SRS-SRU**: handles communication between multiple (up to 40) SRS-FEC cards and the DAQ computer. It also distributes the clock and trigger synchronization to the SRS-FEC cards and send the data fragment to the DAQ PC through Gb Ethernet.

**Need for the PRad GEMs:**

- **Hardware**:
  - 72 SRS-APV FE cards (36 per GEMs) ➞ total of 9184 channels to read out
  - 8 SRS-ADC / SRS-FECs with 9 APVs cards, 3 time samples
  - 2 SRS-SRUs to collected the data from the FECs transfer to the DAQ PC
  - T1pcie: Interface the SRS electronics into JLab DAQ (CODA)
- **Firmware upgrade**
Upgrade of SRS Electronics: Challenges @ 5kHz trigger rate

- Data from APV25 data to FEC cards:
  - 3 time samples: readout mode is about 100 kHz (10 μs), no problem for PRad GEMs readout

- Data from FEC to SRU:
  - 1Gb Ethernet (125 MB/s), data transferred through UDP
  - Rate capability 80 MB/s: 800 Mbps line speed × 80% (for 8b10b line encoding overhead).
  - 3 time samples mode: the APV25 data size per event is ~ 1 kB ⇒ transfer rate @ 5 kHz = 5 MB/s
  - Fixed trigger rate: the data transfer is ~ 60 MB/s with 12 APV25/ FECs (45 MB/s for with 9 APV25)
  - Firmware upgrade (done) for random trigger rate: Implementation of trigger buffering

- Data from SRU to GEM DAQ PC:
  - Default SRU implementation: 1Gb Ethernet (125 MB/s), data transferred through UDP
  - First bottleneck to address: SRU data from 36 APV25 ⇒ minimal transfer rate @ 5 kHz = 180 MB/s
  - Firmware upgrade (done): Implementation of 10 Gb optical link to the GEM DAQ PC

- Data from GEM DAQ PC to PRad DAQ PC:
  - Data are sent from GEM DAQ PC to the PRad DAQ computer via JLab network ⇒ GEM DAQ PC has the TIpcie interface
  - Limited bandwidth to send the data to PRad DAQ PC and write them into disk (APV25 data size @ 5kHz = ~ 400 MB/s)
    - Zero suppression is done in GEM DAQ PC before the transfer of the data to PRad DAQ PC
    - APV25 data size is expected to be reduced by ~ more than a factor 100 to just a couple MB/s
Upgrade of SRS Electronics: 10 GbE link implementation (SRU firmware)
(B. Moffit, JLab DAQ group - B. Raydo, JLab Fast Electronics Group)

Existing SRU firmware from RD51 CERN
- Standard SRU firmware developed for the APV25 electronics with 1Gb Ethernet link
- 10 Gb Optical link firmware previously developed at CERN was available but not compatible with standard firmware

Upgrade of APV25-compatible 10 Gb SRU firmware (Ben Raydo)
- Merging the two firmware and testing with the APV25 electronics

Test Setup
- 36 SRS-APV25 hybrids, connected to 3 FECs (event size 38.5 kB), calibration pulse with internal trigger @ 3 time samples (3TS)
- Rate tests with 1Gb Copper link and upgraded 10 Gb Optical fiber link
- 1Gb SRU: Saturation at ~3.2 kHz (max expected rate before saturation ~ 3.3 kHz)
- 10Gb SRU: linear data transfer speed up to 5.5 kHz ⇒ saturation expected beyond 6 kHz (FEC data to SRU @ 80 MB/s)

![Graph](image)

SRU with 10 Gb & FEC with 1 Gb ⇒ Limitation: data from FEC to SRU
SRU with 1 Gb link ⇒ Limitation: data from SRU to DAQ PC
Upgrade of SRS Electronics: Trigger Buffering (FEC firmware)
(B. Moffit, JLab DAQ group - B. Raydo, JLab Fast Electronics Group)

Non-buffered trigger FEC firmware (original):

- Dead/busy while APV sends triggered data and dead/busy while UDP packets are sent
- For fixed trigger rate, the dead time is basically determined by the UDP data processing (~200 μs)
- For random trigger: the mechanism is inefficient
  - no use of live time with low trigger burst but high trigger burst mean data loss because of dead time

Buffered trigger FEC firmware (new):

- UDP processing of APV data is “de-coupled” from APV sending data
- Dead/busy while APV sends triggered data, no longer dead/busy while UDP packets are sent
- When buffers, holding captured APV for UDP processing in FPGA become full, the FEC create necessary dead/busy time.
- For random trigger, @ high trigger burst, APV data are stocked in buffer and UDP packet is formed during the low trigger burst
- Dead/busy time while APV sends data can be eliminated to improve live time, but requires significant changes to FEC firmware.
Upgrade of SRS Electronics: Source code changes
(B. Moffit, JLab DAQ group - B. Raydo, JLab Fast Electronics Group)

APV25 chip has a 4096 deep sample buffer. When capturing a few time samples (e.g. 3), only a small fraction of the buffer is used. The new firmware makes use of the available buffer to optimize the rate capability of the system.

Old firmware (standard from CERN)

- The firmware performs the following steps sequentially:
  1. receive a trigger and capture the APV25 data
  2. wait for the data to be fully processed by the UDP processor
  3. Then is ready to accept another trigger.

New firmware (upgrade @ JLab)

- circularly writes multiple events along with trigger header information in the existing buffer.
- A new FIFO is added to provide a pointer into the circular buffer to the UPD packet processor.
- The new firmware performs the following steps in parallel:
  1. Receive a trigger, capture APV25 data and is ready to accept another trigger [~ 25 μs]
  2. Check trigger FIFO and build UPD packets independently from step #1 [~ 200 μs]
  3. Check circular buffer and assert BUSY if no more events can be accepted.
- Trigger processing dead time ~ 25 microseconds with up to 10 triggers can be buffered
- BUSY output (NIM Out): Busy Feedback to Trigger Supervisor ⇔ allows for more efficient trigger acceptance without assumptions of FEC processing dead time.
- As a test example, without buffering, we needed up to 70kHz input rate to readout near 5kHz ⇔ dead-time close to 100%. With buffering enabled the input rate could be slightly over 5kHz to readout near 5kHz ⇔ dead-time just a few percent.
Upgrade of SRS Electronics: Tests of trigger buffering
(B. Moffit, JLab DAQ group - B. Raydo, JLab Fast Electronics Group)

Preliminary tests
- 9 / 12 APV25 (ADC channels), on 1 FEC with 3 time samples to the SRU (Expected configuration for PRad)
- Random pulse generator board with both buffered and un-buffered Trigger tested simultaneously
- Additional tests was done with multiple FECs for debugging and troubleshooting
- Cosmic data test setup with the GEM chambers is underway to test the full DAQ with all the changes

Validation @ 5 kHz random trigger rate
- Un-buffered triggers firmware: readout rate of ~2.8 kHz (9 APVs on FEC) ⇒ 44% dead time
- Buffered trigger firmware: readout rate of ~4.25 kHz (9 APVs on FEC) ⇒ 15% dead time, OK for Prad

![Diagram showing readout rate vs. random trigger rate](image-url)
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Integration of SRS into JLab DAQ: PRad DAQ Overview

- PRad DAQ PC
- JLab network Data/Control
- 10 GbE optical fiber
- SRS-SRU
- SRS-FECs Crate
- Linear Sum
  - NIM Crate
  - NIM Crate
  - NIM Crate
  - NIM Crate
- VME Crate
  - Gate for Fastbus ADCs
- Fastbus Crate
  - Trigger to TI slaves
  - Trigger to TI master
- Fastbus Crate
  - SRS-FEC BUSY signal
- Fastbus Crate

- GEM DAQ PC
- TIpcie
- 10 Gb NIC

Logic and Translation

Timing information to JLab discriminators
Integration of SRS into JLab DAQ: **Hardware**
(B. Moffit, JLab DAQ group - B. Raydo, JLab Fast Electronics Group)

- **PClexpress Trigger Interface (TIpcie)**
  - Integrate standard desktop or Server PC with PCIe bus into JLab Pipeline DAQ (CODA)
  - Optimal for the use of multiple cores / threads for data processing and data reduction required for PRad GEMs data
  - PC Hardware allows for multiple network cards (1G, 10G, Infiniband)
  - Runs in Standalone (Master) or Larger-Scale DAQ (Slave).
  - Kernel and userspace driver compatible with EL5, EL6 (i386, x86_64)

- **Interface to the SRS**
  - SRU receive the trigger from the Trigger Supervisor and send BUSY.
  - TIpcie collects data from SRU send to PRad DAQ PC via JLab Network

- **Setup of the high rate (5kHz) test with the TIpcie**
- The back side of the DAQ PC shows:
  - PCIe TI with the blue fiber connection to the TS
  - The twisted pair connections for triggers.
  - The 10 Gb card for data transfer with the links connected (black) to the SRU.
Integration of SRS into JLab DAQ: **Software development**
(B. Moffit, JLab DAQ group - B. Raydo, JLab Fast Electronics Group)

Software libraries for the slow control (B. Moffit)

- C Library written to be used with CODA, **but also works standalone**
- Compatibility: REDHAT EL5, EL6 (i386, x86_64)
- Uses calls to routines for the configuration and readout
  - instead of using system calls to external programs/scripts
  - Still has the capability of reading in the original configuration text files.
  - More 'human' readable, Parameters can be input in any base (hexadecimal, decimal)
- Allows for iterating over several FEC with similar configuration

✓ Done and under test with the cosmic test run

Online monitoring (Xinzhan and Weizhi)

- Before zero suppression (not implemented at the firmware level)
  - Raw APV25 data frames are available for online monitoring during the life time of PRad run
  - During initialisation of all APV25 after DAQ reboot

✓ Done and under test with the cosmic test run

- Zero suppression at software level by CODA Event Builder in the DAQ PC
  - Monitoring of hits and clusterization algorithm for real time characterisation of the GEMs
  - Hits and cluster data will be passed to the CODA Event Recorder to be written into disk

✓ Under development
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Cosmic Tests: Preliminary data
(Xinzhan and Weizhi)

- At last we are seeing cosmic data signal with the GEM chambers
- Ongoing tuning of trigger signal and APV25 data latency for optimization of the setting
- Plan to monitor the stability of the DAQ in the cosmic setup for a few days
- Will after move to the full DAQ system to read out all two chambers and take data for several days for efficiency study
Summary

- Two large PRad GEM chambers built at Uva
  - Preliminary cosmic data test conducted at UVa to test basic performances
  - Delivered to JLab in February and mounted on the support frames in the cosmic setup

- APV25-based SRS is the readout electronics for the Prad GEMs
  - Readout System is based on the SRS electronics developed by the RD51 coll. @ CERN
  - Challenge is to read out 9216 electronic channels (detector strips) @ 5 kHz trigger rate

- Firmware upgrade to allow high rate capability
  - SRU firmware: implementation of 10 Gb optical link for the data transfer from the SRU to the DAQ PC
  - FEC firmware: Implementation of the buffering trigger ⇔ allow 5 kHz trigger rate with limited dead time

- Integration of the SRS into JLab DAQ system
  - JLab custom board T1pcie for the trigger interface between SRS and Prad DAQ system
  - Development of the T1pcie libraries and slow control routines, online monitoring software

- Cosmics setup of the GEM chambers with SRS readout / DAQ
  - First real data from the GEM with the full DAQ chain
  - Test of the DAQ / readout and preliminary study of the chamber detection efficiency

- Goals and plans or the coming weeks before the installation in Hall B
  - Implementation the zero suppression algorithm for online data reduction
  - More tests and checks of the performances of the DAQ and GEM chambers with cosmic setting
Back Up