GEM Detectors Under High Rate at Jefferson Lab

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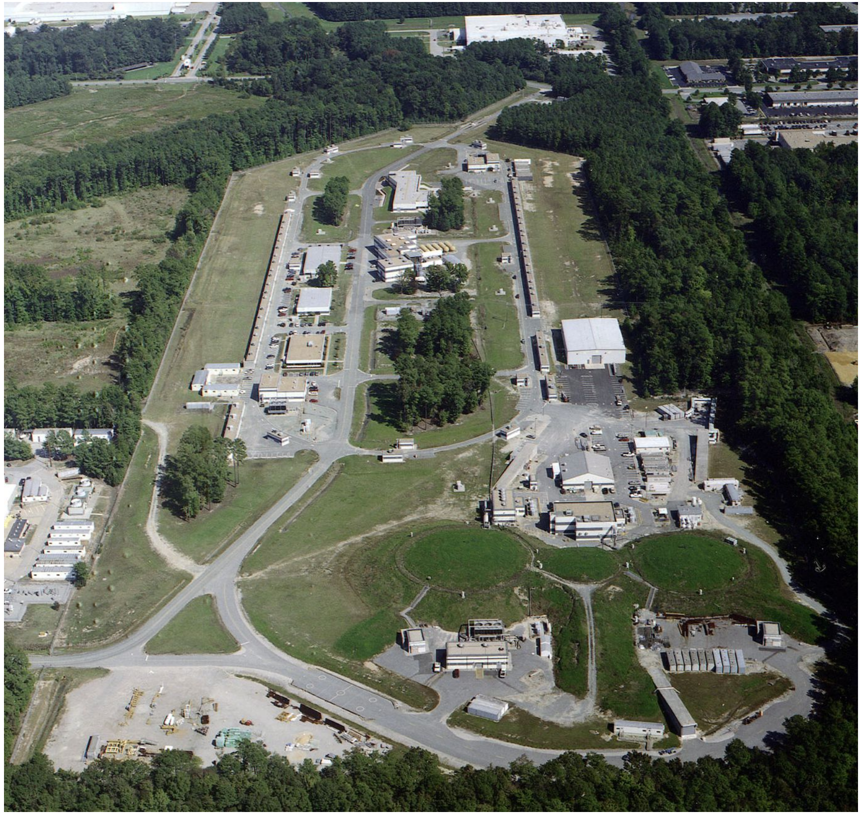
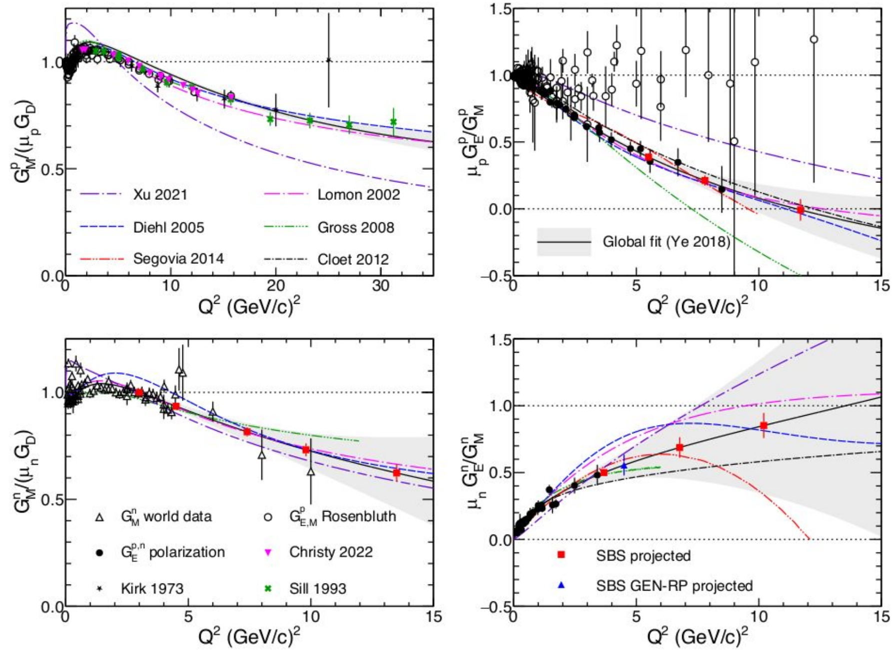
Outline

- GEM detectors for the SBS program at Jefferson Lab
- High rate environment
- Simulation and DAQ efforts
- GEM detectors for the future SoLID program at Jefferson Lab
- Summary



SBS Program at Jefferson Lab

- Measure nucleon form factors at **high Q^2** with **high precision**
- **High Q^2** measurement, **low cross section (quasi-elastic channels)**, requires **high luminosity**

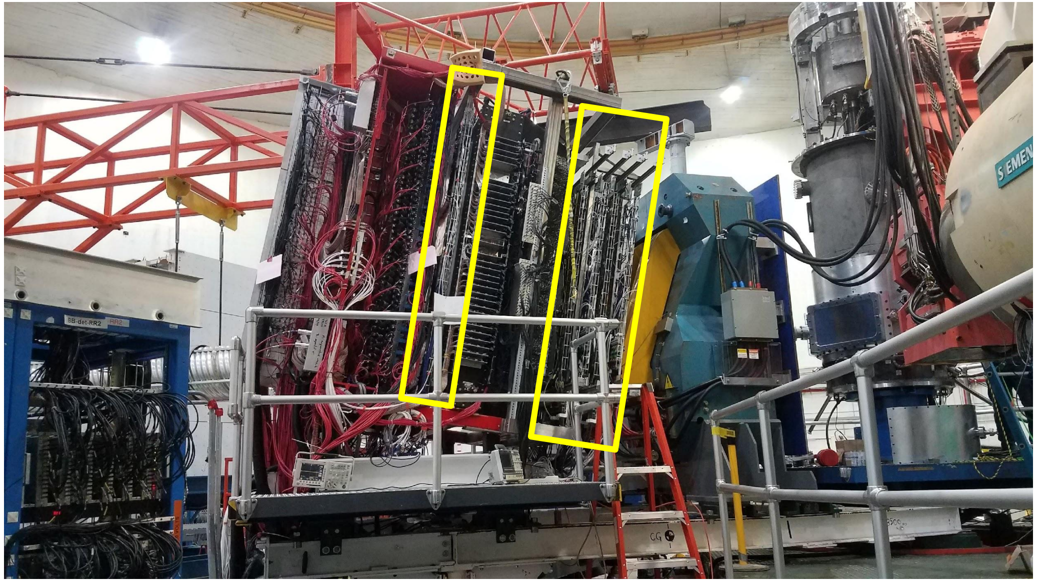


- Started running: Sep. 2021
- GMn/nTPE: Completed Feb. 2022
- GEn Helium-3: Completed Nov. 2023
- GEn-RP: Projected run April 2024
- GEp: Projected run 2024

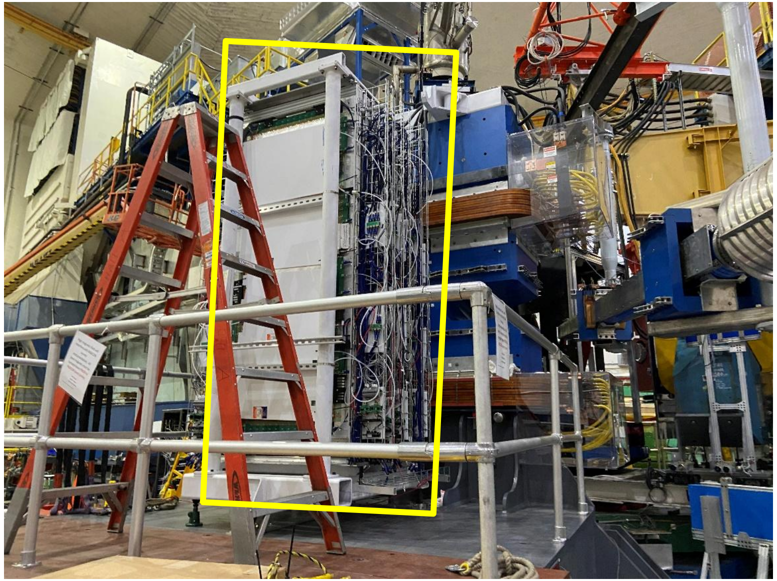
50 Years of QCD
https://arxiv.org/pdf/2212.11107.pdf

GEM Detectors for the SBS Spectrometer

- SBS spectrometers – open geometry configuration
- Luminosity up to **5x10^{38}**
- GEM Detectors to handle the high rate
- Two detector-package arms: electron arm + hadron arm
- For **SBS-GEn**:
  - **5 layers** in BB electron arm
  - **8 layers** in SBS handron arm



Bigbite electron arm



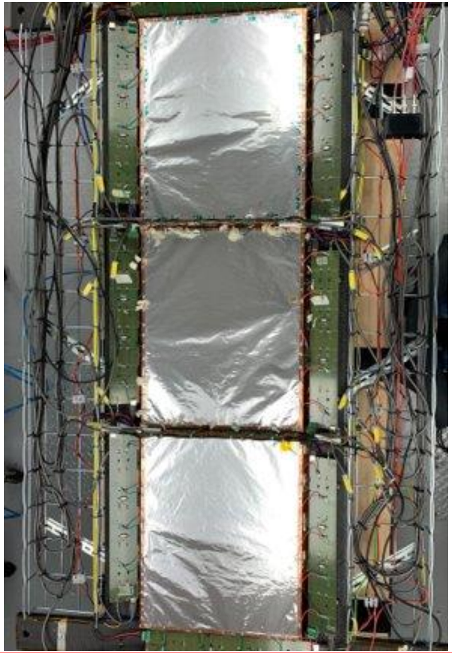
Super Bigbite hadron arm

GEM Detectors in BigBite Spectrometer

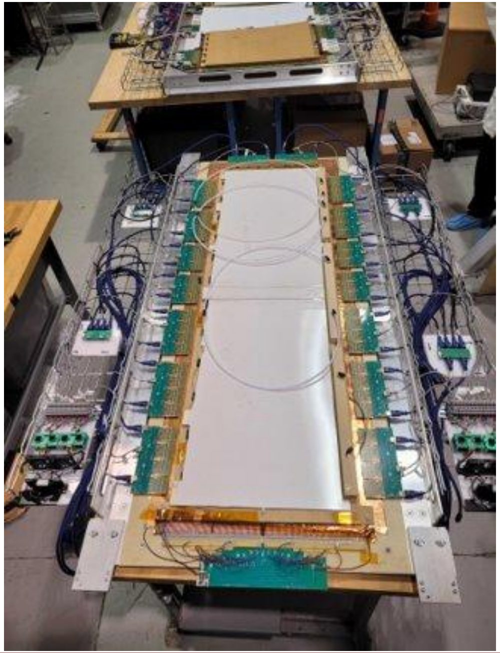
40x150 cm^2 layers, made of 3 40X50 GEM modules

40x150 cm^2 layers, made of a single module, no dead area in active area

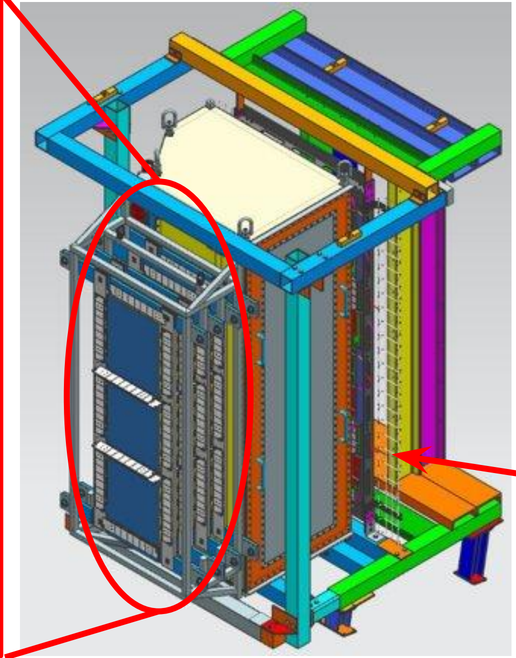
60x200 cm^2 layers, made of 4 60x50 cm^2 GEM Modules

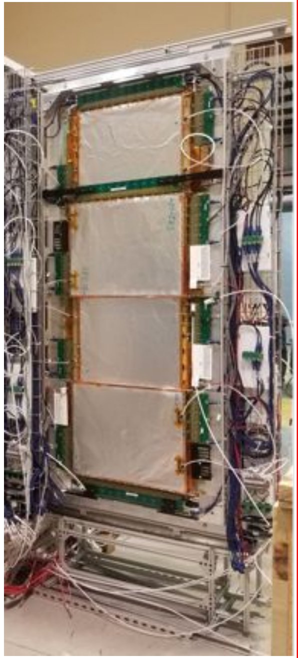


INFN XY Layer



UVA UV Layer

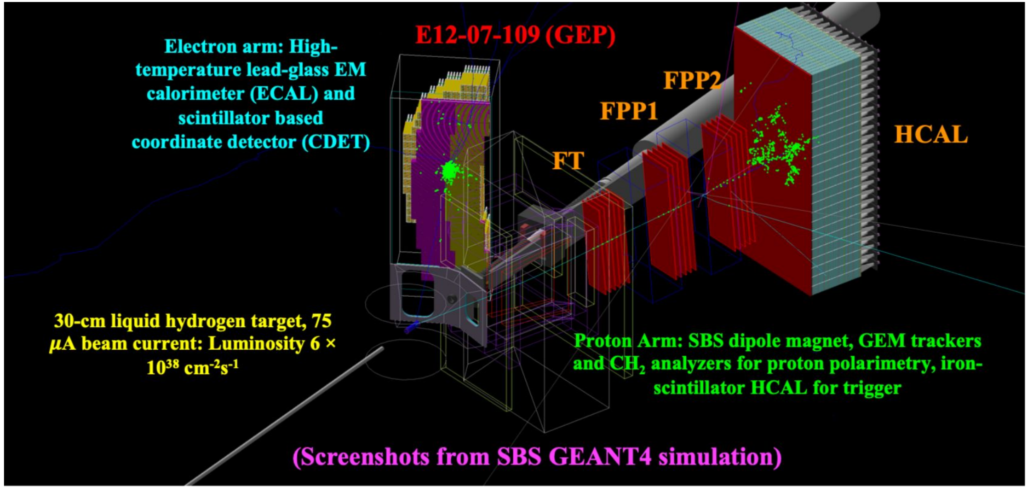




UVA XY Layer

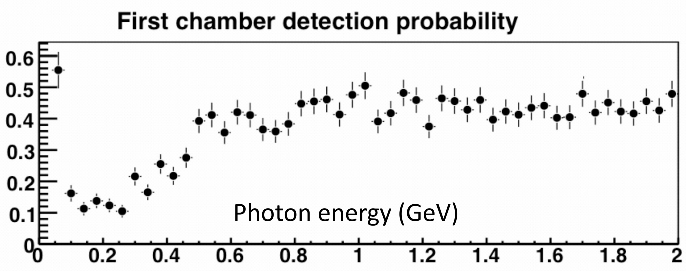
Rate Requirements for SBS GEM Detectors

- ❑ Most challenging experiment – GEp – coming in 2024
- ❑ High background rate (~275 kHz/cm^2), mainly from low energy photon conversion
- ❑ Large data volume from high number of readout channels



GEp Setup

Photon conversion rate from G4SBS on a standard COMPASS-structure triple GEM Detector – plot taken from SBS CDR

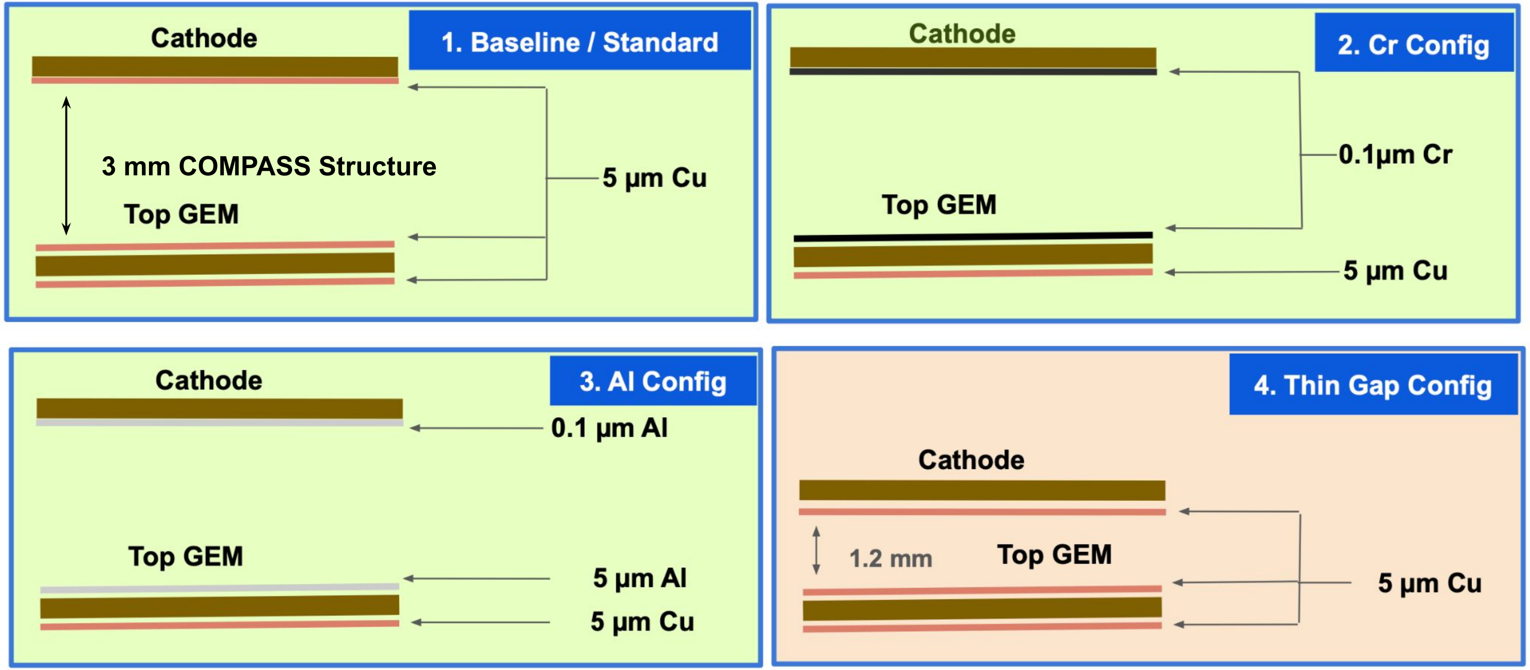


- One solution is to optimize the GEM detector structure
- Reduce the photon conversion rate on GEM detectors

Geant4 Simulation on Optimizing GEM Foil/Detector Structure

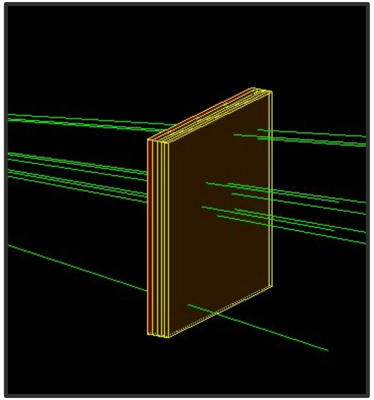
- Effort to reduce the photon conversion rate on GEM detectors
- Simulation on different GEM foil/detector structure

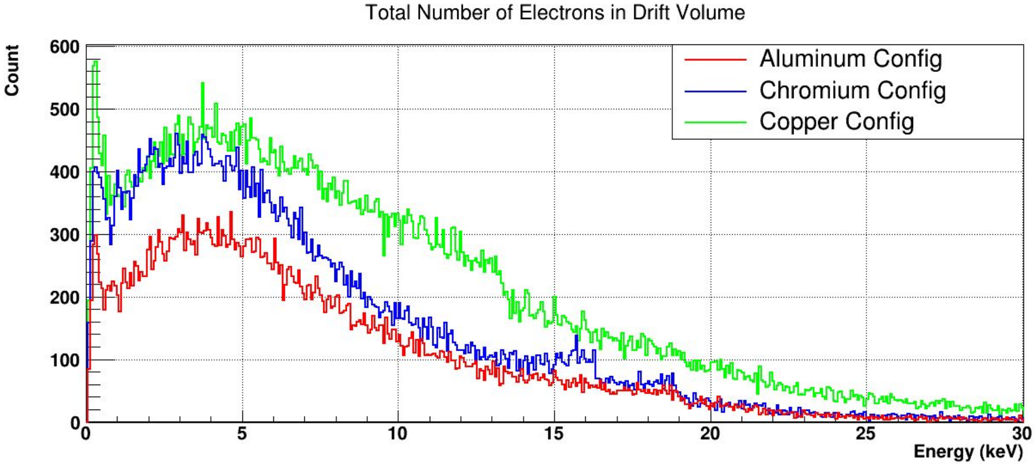
See Kondo's Monday talk on thin-gap beam test results



Geant4 Simulation on Optimizing GEM Foil/Detector Structure

- ❑ Prototypes of different configurations completed
- ❑ Under test using x-ray
- ❑ Similar setup in Geant4
- ❑ Simulation results shows an improved results on Cr/Al cathode foils

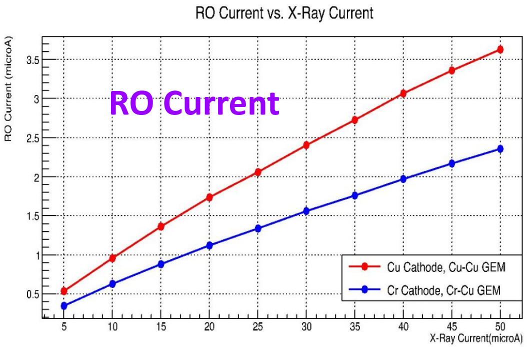


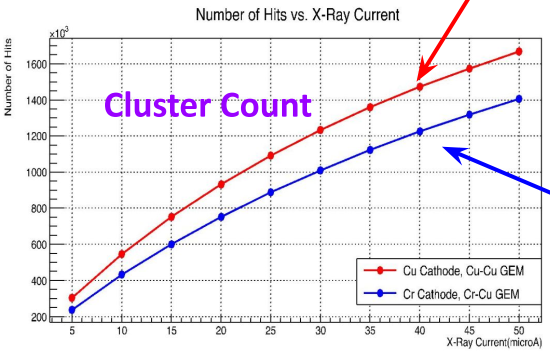


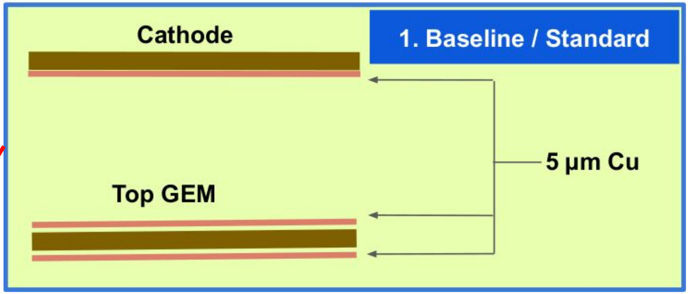
UVA x-ray

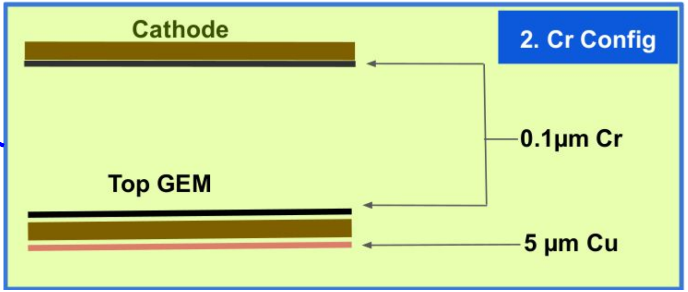
Geant4 Simulation on Optimizing GEM Foil/Detector Structure

- Photon conversion – cathode foil, drift region (thin-gap)
- Experimental measurements
  - **Current from readout board**
  - **cluster count** under **a fixed amount of time**
- Significant photon-converted cluster count reduction: **16%** for **Cr GEM detectors**



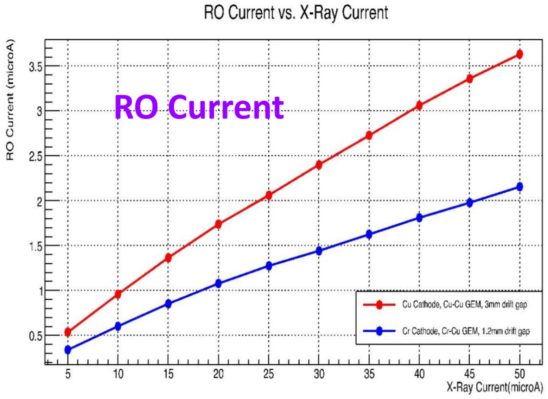


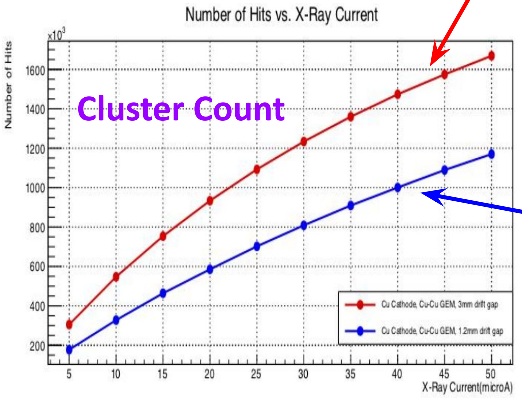


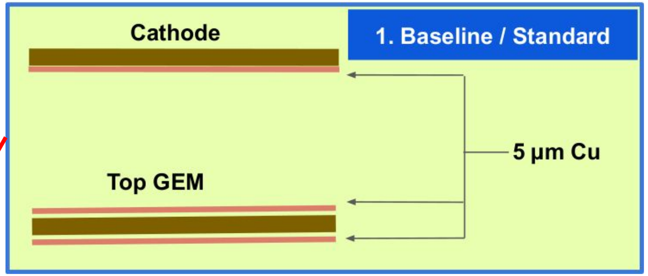


Geant4 Simulation on Optimizing GEM Foil/Detector Structure

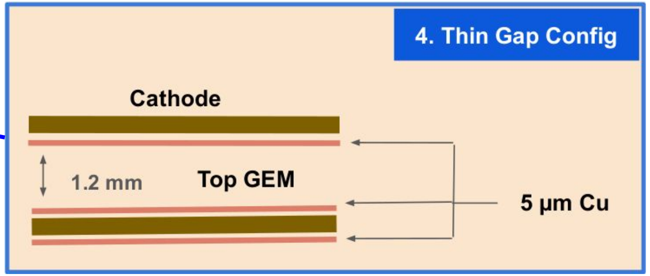
- Photon conversion – cathode foil, drift region (thin-gap)
- Experimental measurements
  - **Current from readout board**
  - **cluster count** under **a fixed amount of time**
- Significant photon-converted cluster count reduction: **30%** for **Thin-Gap GEM detectors**
- Simulation study on-going – Garfield / Geant4







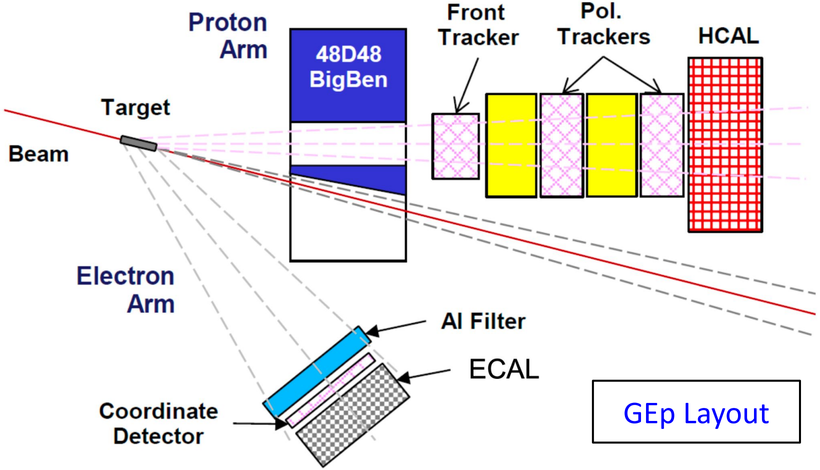
See Kondo's Monday talk on thin-gap beam test results



DAQ Challenges for the SBS program

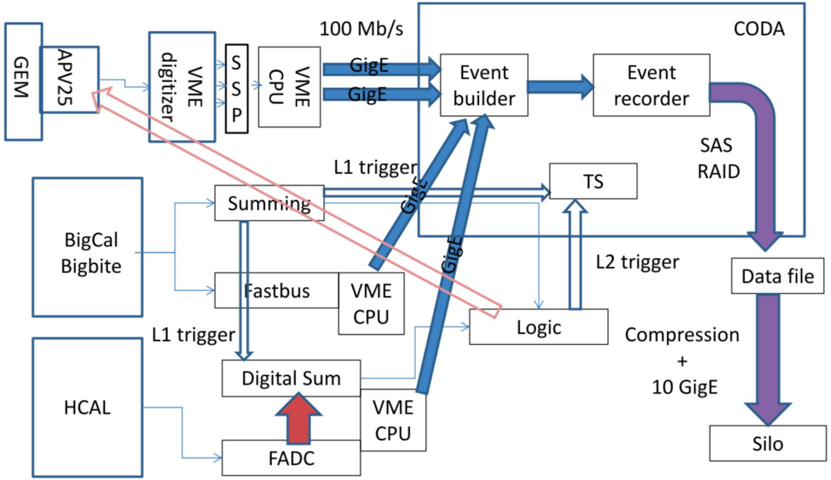
- **Most challenging experiment – GEp – RO channels**

GEp Detectors	Channels	Readout	Type
SBS Hadron Arm Front Tracker (8 GEM Layers) Rear Tracker (8 GEM Layers) HCal	 **75,776** **90,112** 288	 **MPD/APV** **MPD/APV** FADC250	 **VTP** **VTP** VME
BigBite Electron Arm ECal ECal Sum CDET	 1710 219 2688	 ADCs 1881M TDCs 1877S TDCs 1877S	 Fastbus Fastbus Fastbus



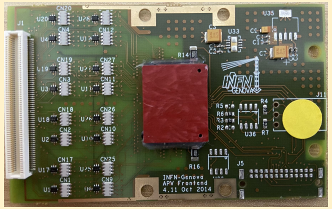
GEp Layout

- GEMs take the majority (**>95%**) of readout channels
  - Expected Singles Hit Rates (front tracker: 275 kHz/cm^2)
  - Cluster size (MIPs) : 2.5 strips – **30% strip occupancy**
  - **8 layers for tracking system, minimum 4 layers fired out of 8 : tracking eff. ~75%**
  - Samples/Event: 6
  - **Trigger Rate: 5 kHz**



GEp DAQ data flow – **plot Courtesy of Evaristo Cisbani – INFN**

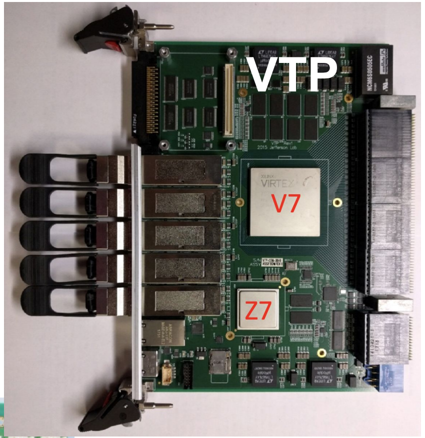
Data Path for the SBS GEM DAQ



- **128 analog ch / APV25 ASIC**
- **3.4 us trigger latency** (analog pipeline)
- Capable of sampling signal at 40 MHz
- Multiplexed analog output (**100 kHz readout rate**)

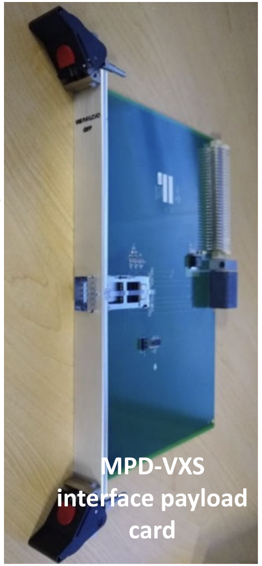
MPD modules designed for SBS Program

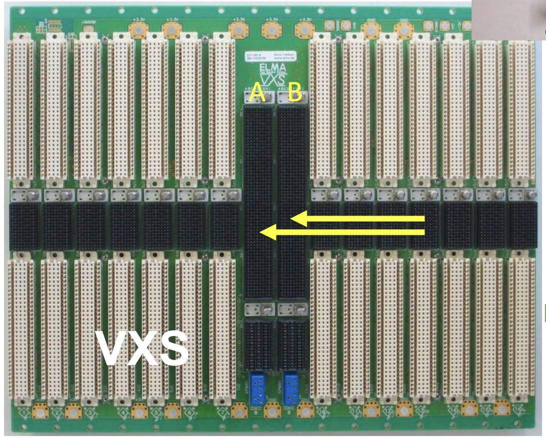
- Up to 16 APV cards on a single module
- 2 ns time resolution (APV clock synchronization)
- Arriga GX FPGA 128 MB DDR2-RAM
- **Online zero suppression**



HDMI

Optical fiber 2Gbps





VXS bus – 20 Gbps bandwidth (4 lanes)

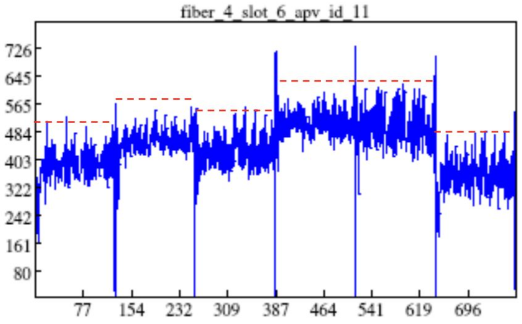
Aurora Protocol

CODA

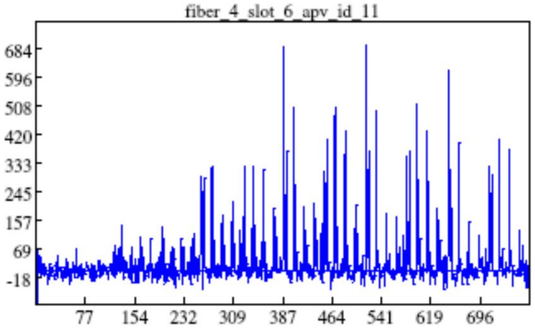
Paolo, Evaristo (INFN)

Online Zero Suppression

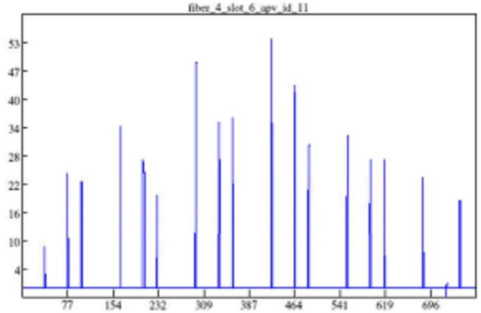
- ❑ Online zero suppression algorithm implemented on MPD module **on-bard FPGA**
- ❑ 3 different algorithms developed (Sorting, Danning, Histogramming)
  - ❑ First 2 algorithms developed by UVA group
  - ❑ Danning Algorithm has been successfully implemented on the FPGA firmware – production algorithm for GMn, GEn experiments – Ben Raydo, JLab
  - ❑ Histogramming algorithm (Andrew Puckett, UConn) to be implemented for GEp experiment – optimization for unexpected polarity-inverted "signals"
- ❑ Average of ~70% data reduction rate for GMn – depends on occupancy



Raw APV Data Frame



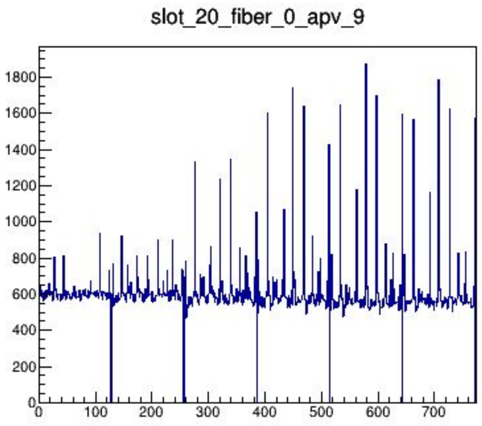
Offset & Common Mode Correction



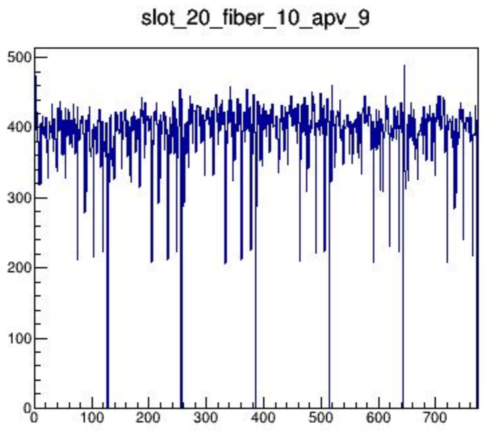
Zero Suppression

Observations Encountered during SBS-GMn Run

- ❑ New observations on the performance of GEM electronics – inverted polarity (***signals??***)
- ❑ On-going investigation effort for the causes (only observed this in the experimental Hall)



Normal APV raw frame



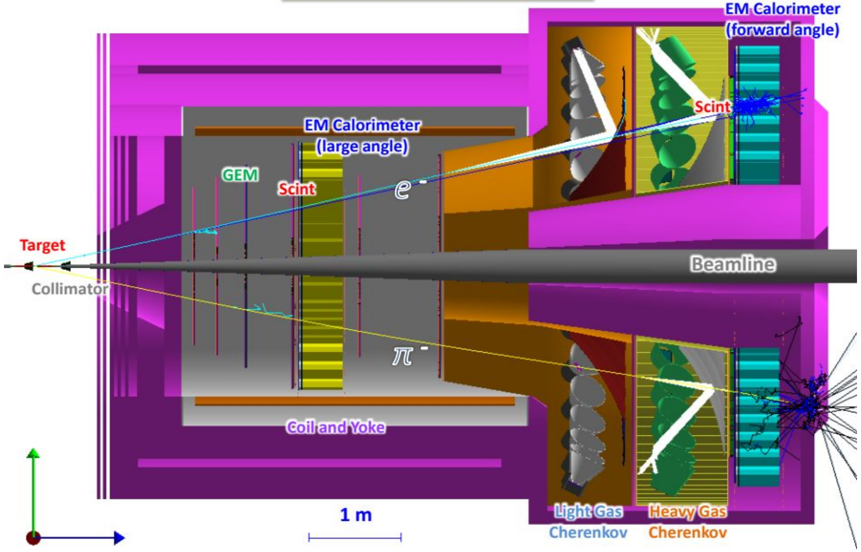
Polarity inverted

Preliminary study shows non correlation with real signals

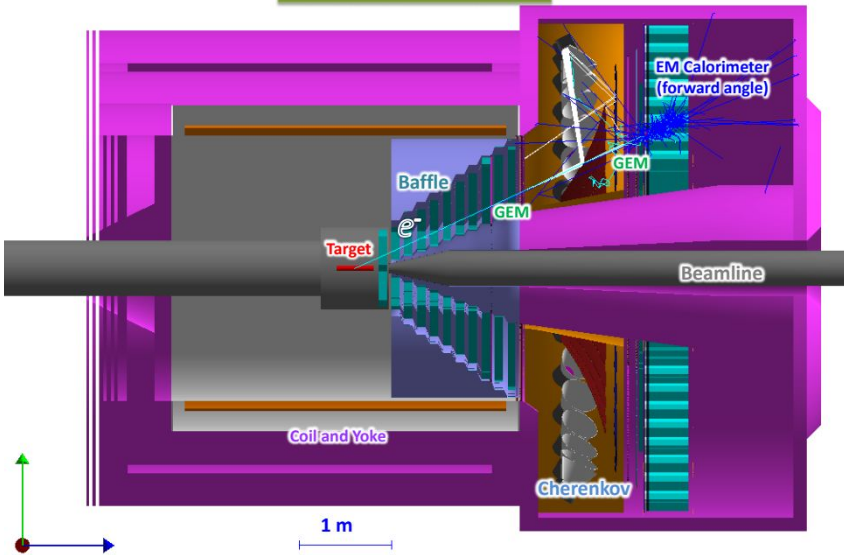
GEM Detectors for the SoLID program

- Study nucleon 3D structure using the upgraded 12 GeV CEBAF
- Two major configurations – PVDIS, SIDIS – detectors interchangeable
- Even larger GEM detector assembly, more than 200 modules

SoLID (SIDIS and J/ψ)

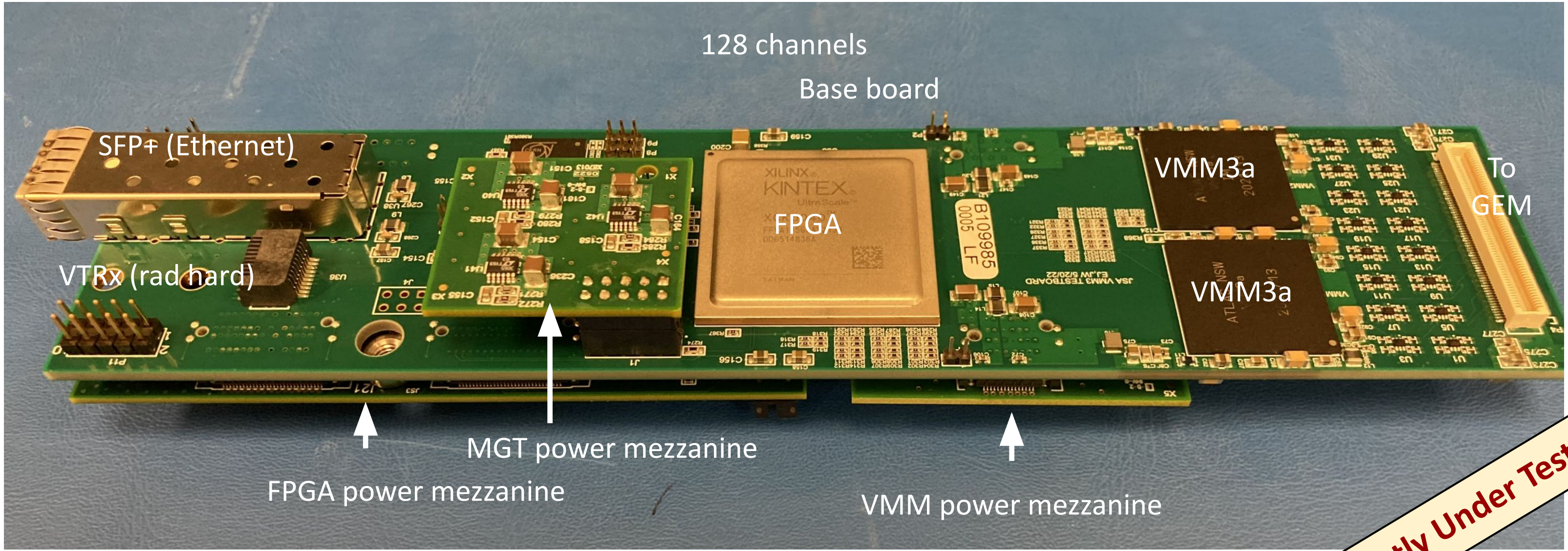


SoLID (PVDIS)



DAQ for SoLID GEM Detectors – More Challenging

- ❑ High luminosity (**up to 10^{39}**) : **~ 500 kHz/cm^2** background rate
- ❑ DAQ trigger rate: ~ several hundreds of kHz
- ❑ Reduce data rate → VMM3a chip, **6-bit** ADC readout
- ❑ **Streaming readout – on plan for SoLID**



Board Dimension: 50 mm x 215 mm

Currently Under Test at JLab

Summary

- Spectrometers at Jefferson Lab require operating GEM detectors under high-rate environments
- Many techniques have been (are going to be) implemented to accommodate the high-rate situation
  - DAQ optimization
  - GEM Detector R&D – simulation study / prototype testing
  - Improved GEM Detector HV system, ……
- Up To now, good and stable operation of GEM Detectors for **year-long** continuous running
- New observations have been identified, investigation on going

Acknowledgement

Sincere thanks to:

- The SBS Collaboration
- The MPGD community for thorough R&D efforts
- Continuous support from CERN/PCB workshop
- US Department of Energy, Office of science, Office of Nuclear physics award number DE-FG02-03ER41240

Backup Slides

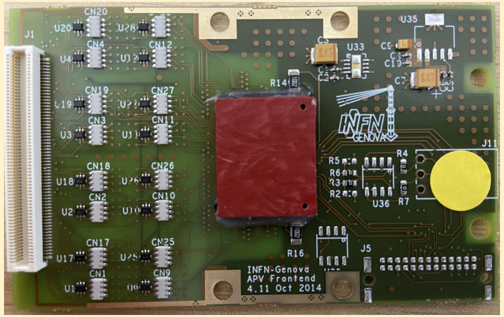
GEM DAQ Readout Limits

MPD-VTP readout limits

- ❑ 15 APVs per MPD, 128 strips per APV, 6 time samples, 32-bit word per 2 samples ⟶ MPD event size: ~23 kBytes
- ❑ MPD to Payload Card data bandwidth: Optical Fiber/QSFP+ transceiver ⟶ up to 2 Gbps (Not a bottleneck)
- ❑ 988 APVs in total, so total event size : ~1.5 MBytes / event
- ❑ Distributed to 3 VXS crates: ~0.5 MBytes per crate
- ❑ VXS bandwidth 20 Gbps (2.5 GB/s): max trigger rate ~5 KHz
- ❑ Data rate further reduced with online zero suppression
- ❑ GEp will implement the Calorimeter-cluster-based-cut algorithm on VTP FPGA firmware to further reduce the data rate

SBS GEM MPD modules in VME Crates

Readout Electronics for the SBS GEM detectors



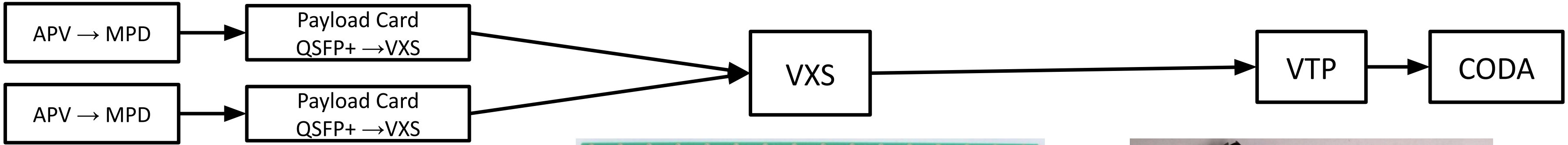
- **128 analog ch / APV25 ASIC**
- **3.4 us trigger latency** (analog pipeline)
- Capable of sampling signal at 40 MHz
- Multiplexed analog output (**100 kHz readout rate**)

MPD (multi-purpose digitizer) designed for SBS program

- **Up to 16 APV25 cards (2048 chs) on a single MPD board (parallel readout)**
- Altera Arriga Gx FPGA/RAM: DDR2 (128 MB)
- **Optical Fiber Link Interface (Aurora ~2 Gbps peak)**
- 110 MHz system clock and Front panel coax clock
- Used HDMI-A for analog and digital signals
- **VME/32, VME64, VME-VXS compliant (up to 200 MB/s peak)**
- 4 high speed line on the VXS available for data transfer
- Firmware v. 4.0 (74% resources):
  - Finite-Impulse-Response Filter (16 parameters)
  - **Zero Suppression (sparse readout)**
  - Remote Configuration
  - ~2 ns trigger time resolution
  - VME/Optical Fiber simultaneous implementation

Paolo, Evaristo – INFN

Data Path for the SBS GEM Detectors



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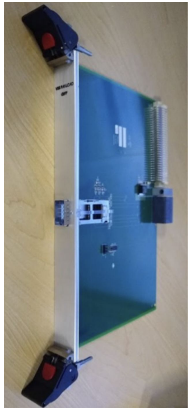
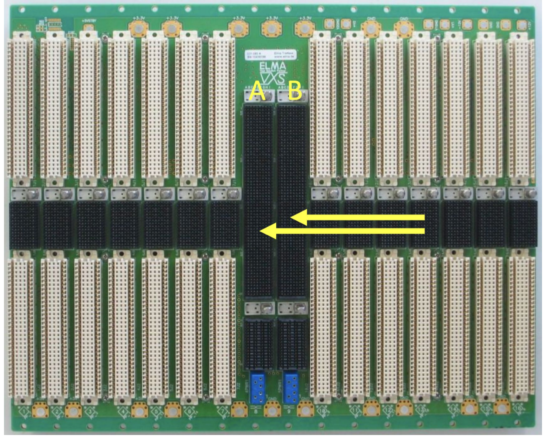
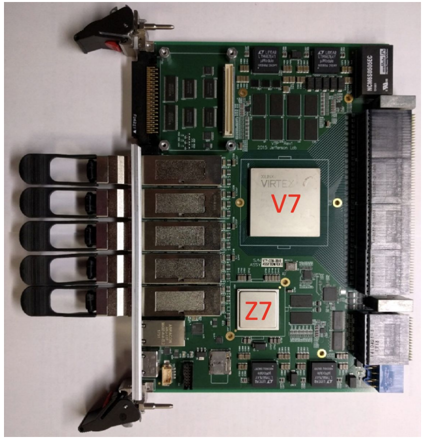
Up to 32 MPD modules Per VXS crate







Payload card

- QSFP+ to VXS converter
- Simple direct serial link
- Access to VTP for MPD modules

Plots Courtesy of Ben Raydo – JLab

VXS Bus

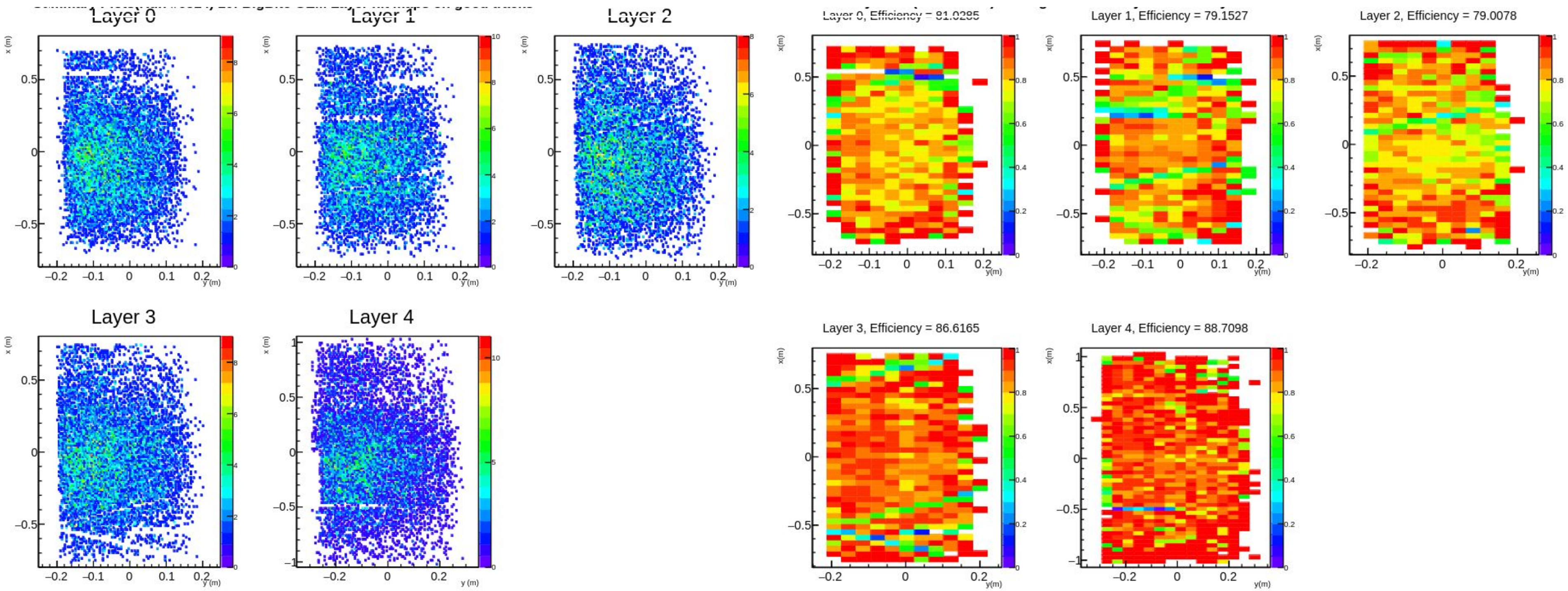
- JLab standardized on this technology for its 12 GeV upgrade
- **Up to 20 Gbps (4 lanes) for each payload to the two switch slots (A & B)**
- Easy distribution of trigger or low jitter clock to all modules in the crate

VTP

- VXS Trigger Processor
- Triggered or streaming readout from all payload modules in parallel
- **More computing resources: powerful on-bard FPGA Xilinx Vertex 7 FPGA**
- Linux OS on the Zync 7030 SOC

SBS GEM Detector Overall Performance

- ❑ Stable operation for 3-years-long continuous running
- ❑ Overall efficiency > 80% from tracking (preliminary results)



Beamtest for Thin-Gap GEM Prototype at Fermilab

- Resolution and efficiency for Thin-Gap GEM prototypes tested at Fermilab using 120 GeV proton beam
- Thin-Gap can significantly improve position resolution at large scattering angle (45 degree)
- Did not see a significant efficiency drop on Thin-Gap prototypes
  - Efficiency drop can be further mitigated by a better HV design, a heavier working gas: $KrCO_2$