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MPGDs for Nuclear Physics Experiments

Matt Posik

Temple University

[White Paper 2: arXiv 2203.06309](https://arxiv.org/abs/2203.06309)

US-Based MPGD User Facility

MPGDs for nuclear physics experiments and a proposed MPGD center of excellence

8:30 AM - 8:50 AM
238 (HUB)
23D

Presenter Matt Posik

US-based MPGD User facility (Video presentation)

11:00 AM - 11:20 AM
238 (HUB)
23D

Presenter Kondo Gnanvo

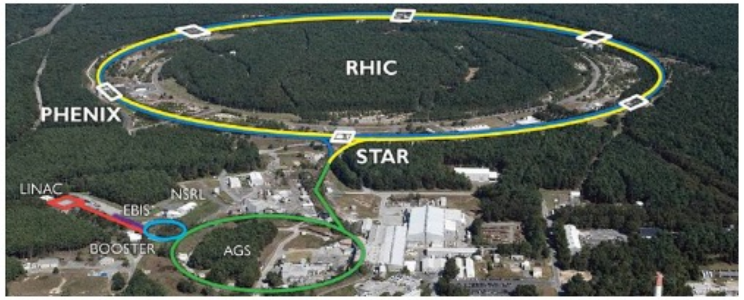
Nuclear Physics Experiments

MPGDs in Nuclear Physics

- Many DOE funded nuclear facilities are making use of state-of-the-art MPGDs in their experiments and will continue to push MPGD development in future experiments.
- These facilities are complimentary
  - Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU) uses rare isotope beams
  - Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab (JLAB) uses polarized electron beam on fixed targets
  - Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab (BNL) will host the future EIC where polarized electrons will collide with polarized protons and ions

Continuous Electron Beam Accelerator Facility (CEBAF)

Facility for Rare Isotope Beams (FRIB)



Relativistic Heavy Ion Collider (RHIC)

Nuclear Physics and High Energy Physics

Common MPGD Challenges

- High energy physics (HEP) and nuclear physics (NP) share many common challenges in MPGD development
  - Large area
  - High-rate capabilities
  - Radiation hardness
  - Space point resolution

NP Specific Challenges

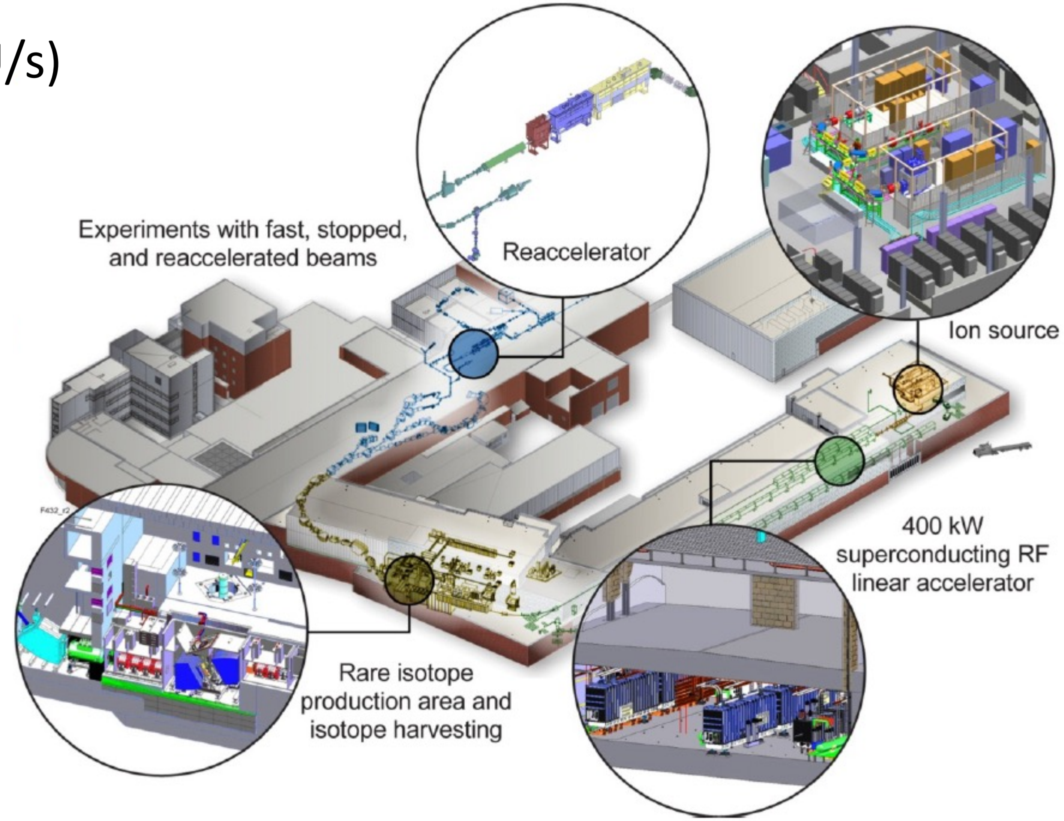
- Major LHC experiments (ATLAS, CMS, LHCb) in HEP typically use MPGD technologies as muon chambers or as readout planes for TPCs
- Many NP experiments use MPGDs as tracking detectors in the spectrometer.
- Difference in applications leads to some NP specific R&D
  - Requirements on detector design
  - Choice of material and support structure to minimize material budget
  - Radiation environment: NP experiment environments range from low-rate and low radiation background to high-rate ($\approx$MHz/cm^2) and radiation harsh environments.

About the Facility for Rare Isotope Beams (FRIB)

Slide courtesy of Marco Cortesi

FRIB

- Funded with financial assistance from DOE Office of Science (DOE–SC) with cost share and contributions from Michigan State University (MSU) & State of Michigan.
- Key features is 200 MeV/u 400 kW beam power (5×10^{13} ^{238}U/s)
  - Tremendous discovery potential: 80% coverage Z < 82
- Separation of isotopes in-flight
- Science program requires range of energies
  - fast, stopped, and reaccelerated beams
- Upgradable to 400 MeV/u
- Is a multi-user facility
  - ~1,600 users
  - Members are from: 124 US colleges/universities, 13 National Labs, and 52 countries



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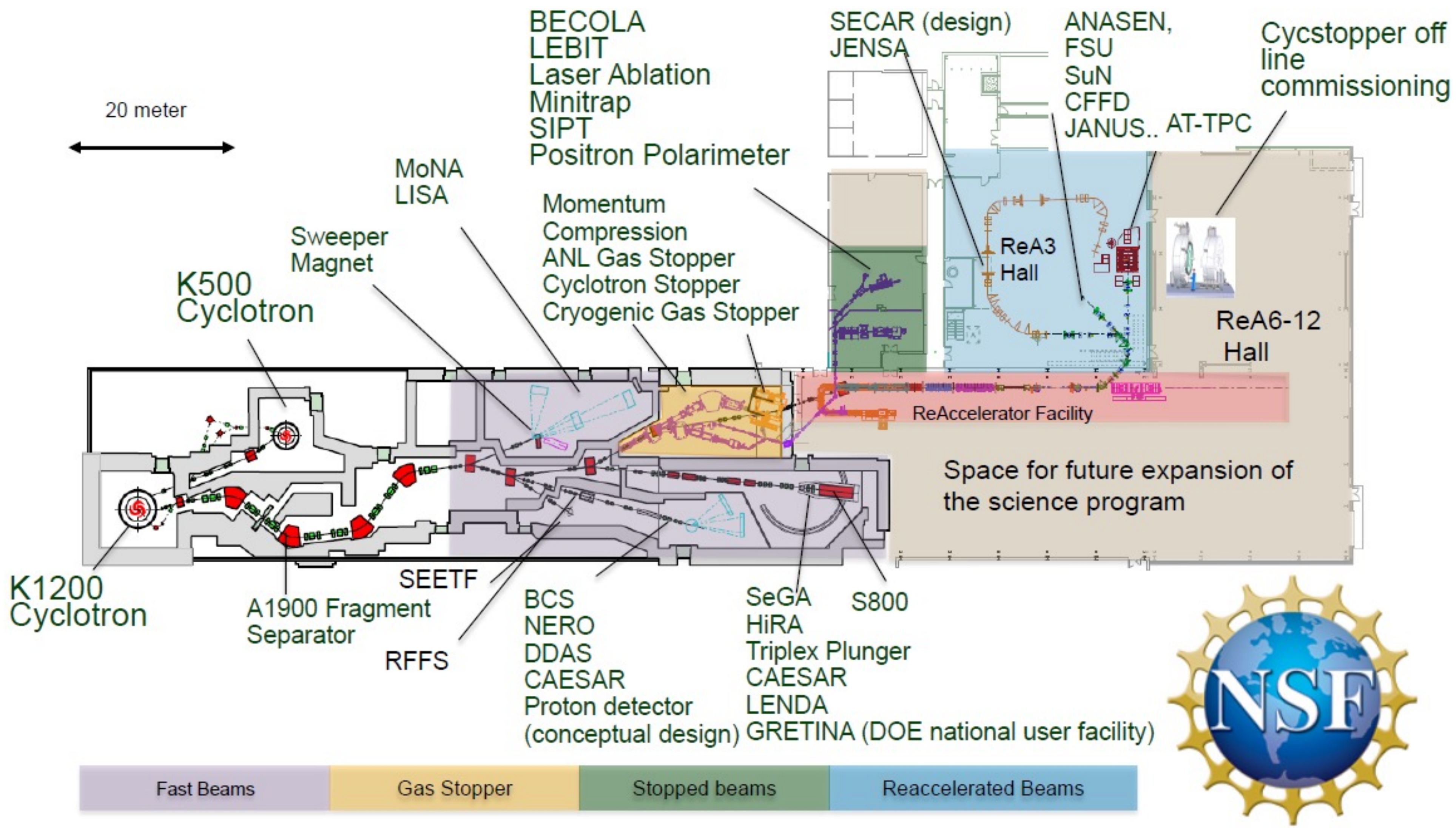
Pre-FRIB Science Opportunities at NSCL

Slide courtesy of Marco Cortesi



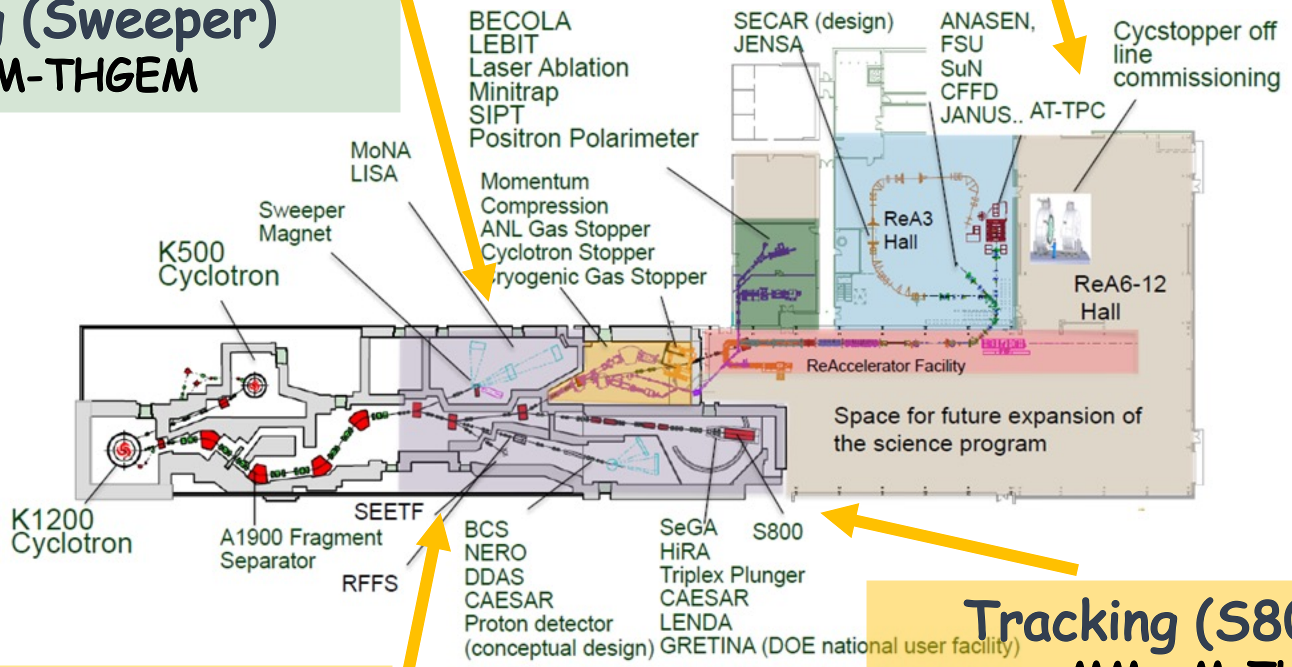
Applications of MPGDs @ FRIB

Slide courtesy of Marco Cortesi

MoNA GPM readout & Missing-Mass Measurement
M-THGEM, MM-THGEM

Tracking (Sweeper)
MM + M-THGEM

AT-TPC (ReA3-ReA6)
MM+3-Layer M-THGEM



R&D project

In operation

GADGET (Stopped beam)
Tracking + γ-tagging
MM-based readout

Tracking (S800/HRS)
MM + M-THGEM

Calorimetry (S800/HRS)
LAr optical readout based MPGD

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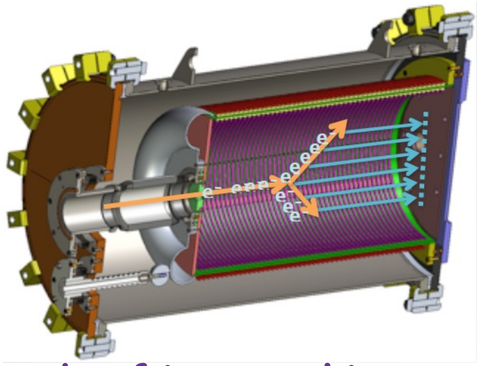
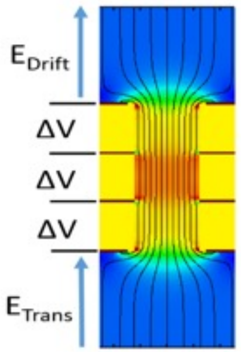
Slide courtesy of Marco Cortesi

Goal

- Development of new hole-based readouts (Multi-layer THGEMs) for operation in pure elemental gas (Active-Target TPC), & for low pressure drift chambers (Beam Tracking)



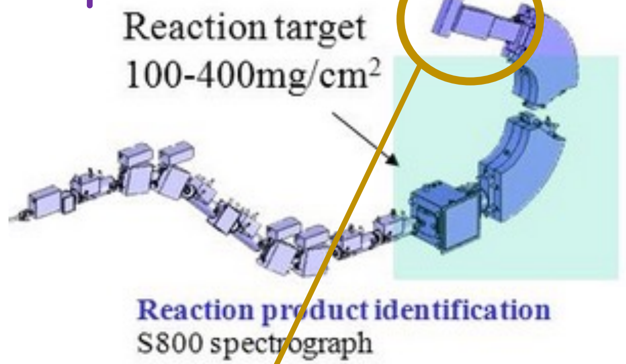
Study of inverse-kinematic nuclear reactions with AT-TPC

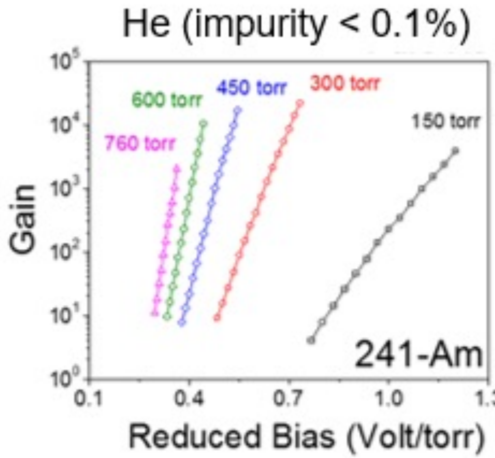


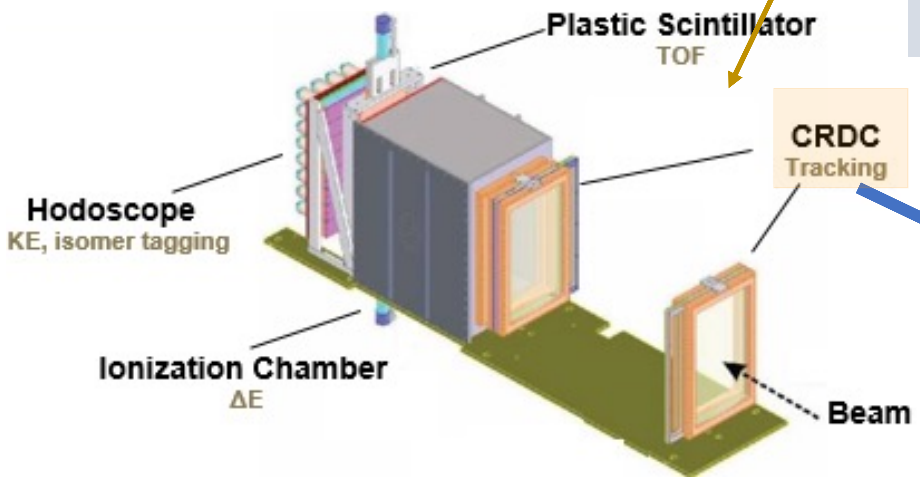
3-Layer M-THGEM

Radioactive isotope Fast Beam experiment

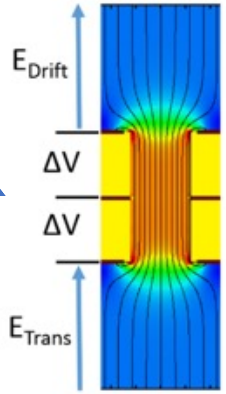
Focal Plane







2-Layer M-THGEM



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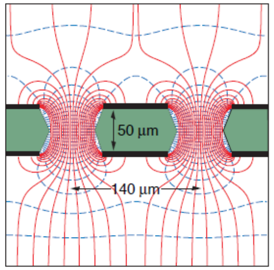
M-THGEM Derived Structures: MM-TGEM

Slide courtesy of Marco Cortesi

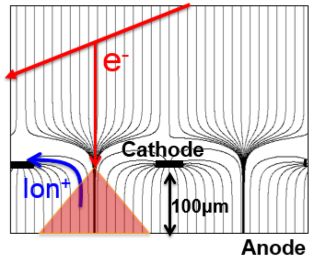
Goal

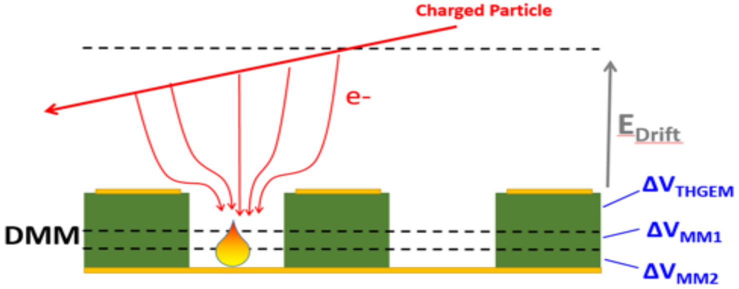
- Double Micromegas (for Low IBF) supported by M-THGEM structure (for large area coverage and good gas avalanche gap uniformity)

GEM like structure

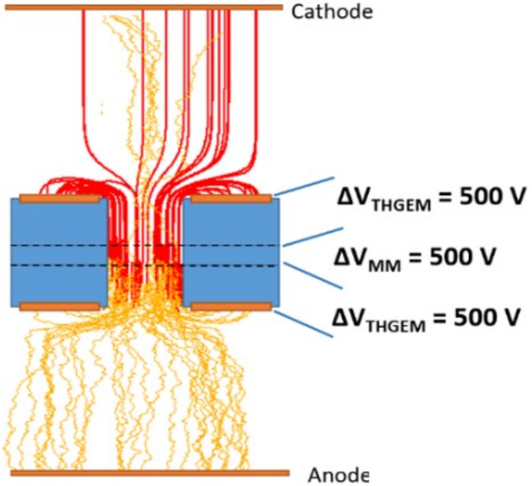


Micromegas (MM)

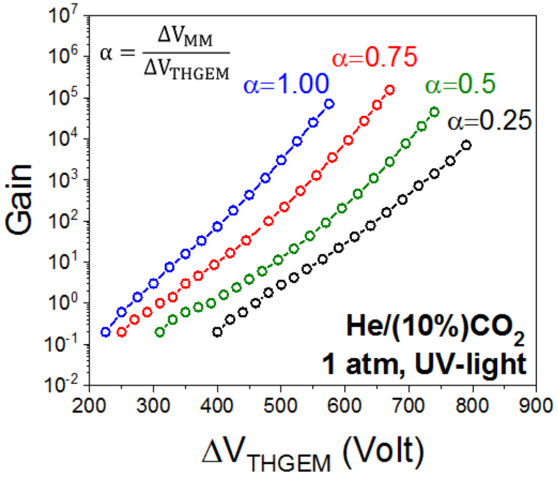


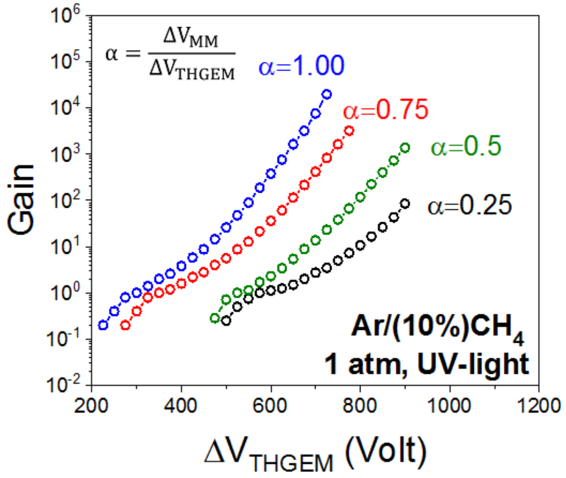


Single MM-THGEM



Effective gain (preliminary results)





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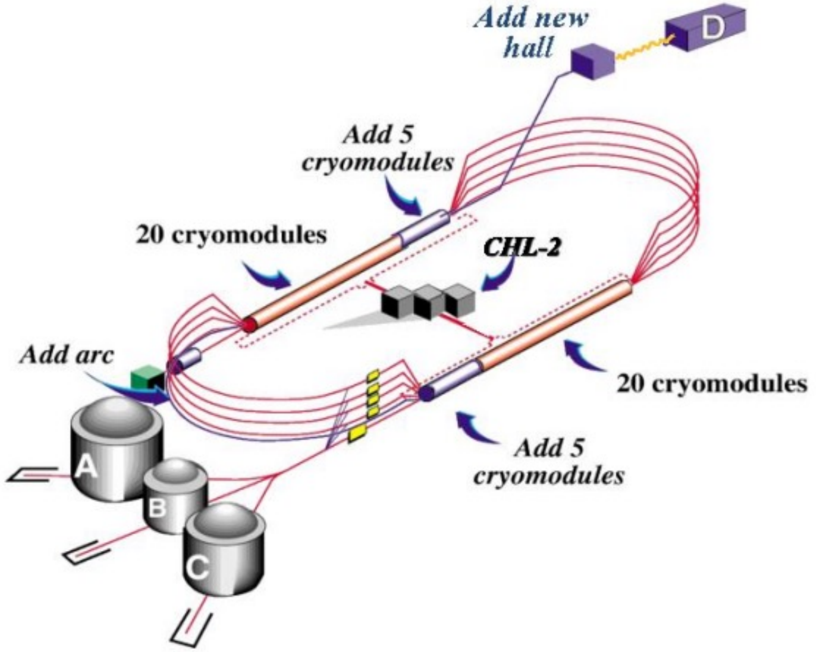
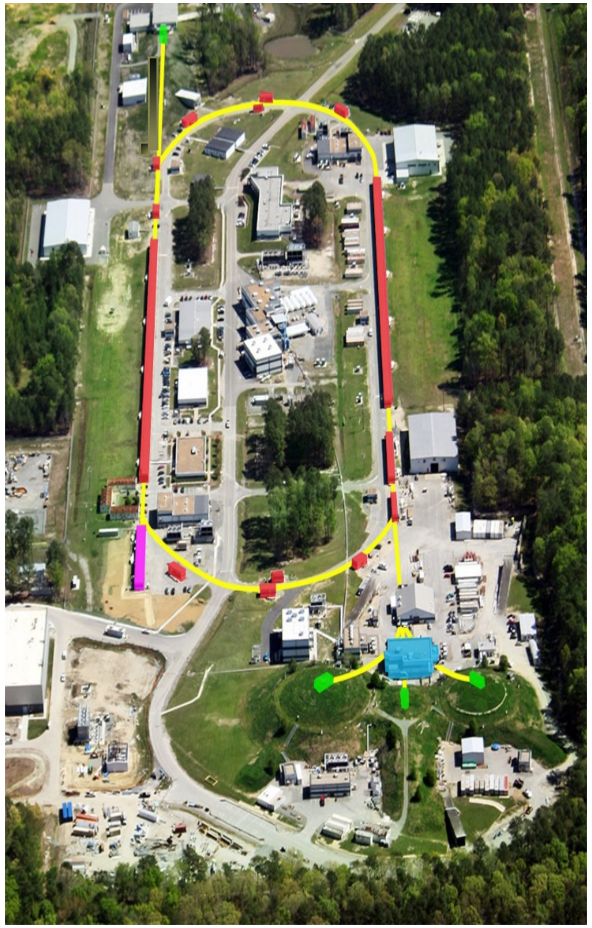
About the Continuous Electron Beam Accelerator Facility (CEBAF)

[Slide adapted from INCFP 2019, Allison Lung]

CEBAF at Jefferson Lab (JLab)

- Nuclear experiments at ultra-high luminosities, up to 10^{39} electrons-nucleons / cm^2/s
- World-record for polarized electron beams ~90%
- E_{max} =12 GeV, I_{max} = 90 μA
- Highest intensity tagged photon beam at 9 GeV
- Unprecedented stability and control of beam
- Ability to deliver a range of beam energies and currents to multiple experimental halls simultaneously
- Large user facility with many users (~1,700)
    - US and international user base





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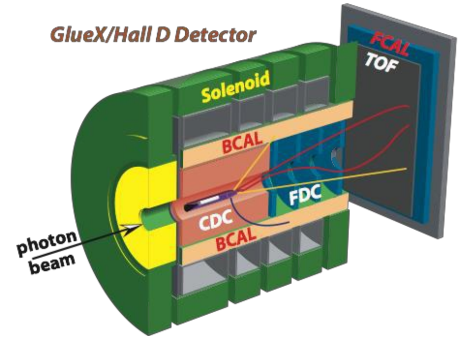
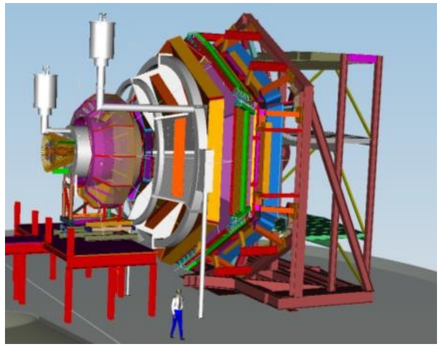
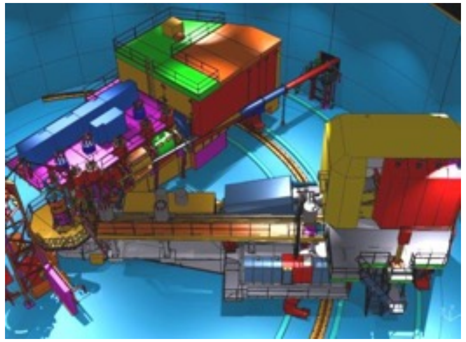
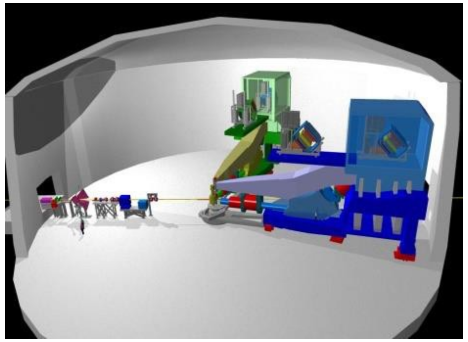
JLab Experiments and Detectors

Slide from INCFP 2019, Allison Lung









<table>
<tr><th>Hall D</th><th>Hall B</th><th>Hall C</th><th>Hall A</th></tr>
<tr><td>excellent hermeticity</td><td>luminosity 10^{35}</td><td>energy reach</td><td rowspan="2">large experiment installation</td></tr>
<tr><td>polarized photons</td><td>hermeticity</td><td>precision</td></tr>
<tr><td>E_γ ~8.5-9 GeV</td><td colspan="3">11 GeV beamline</td></tr>
<tr><td>10^8 photons/s</td><td colspan="3">target flexibility</td></tr>
<tr><td colspan="2">good momentum/angle resolution</td><td colspan="2">excellent momentum resolution</td></tr>
<tr><td colspan="2">high multiplicity reconstruction</td><td colspan="2">luminosity up to 10^{39}</td></tr>
<tr><td colspan="4">particle ID</td></tr>
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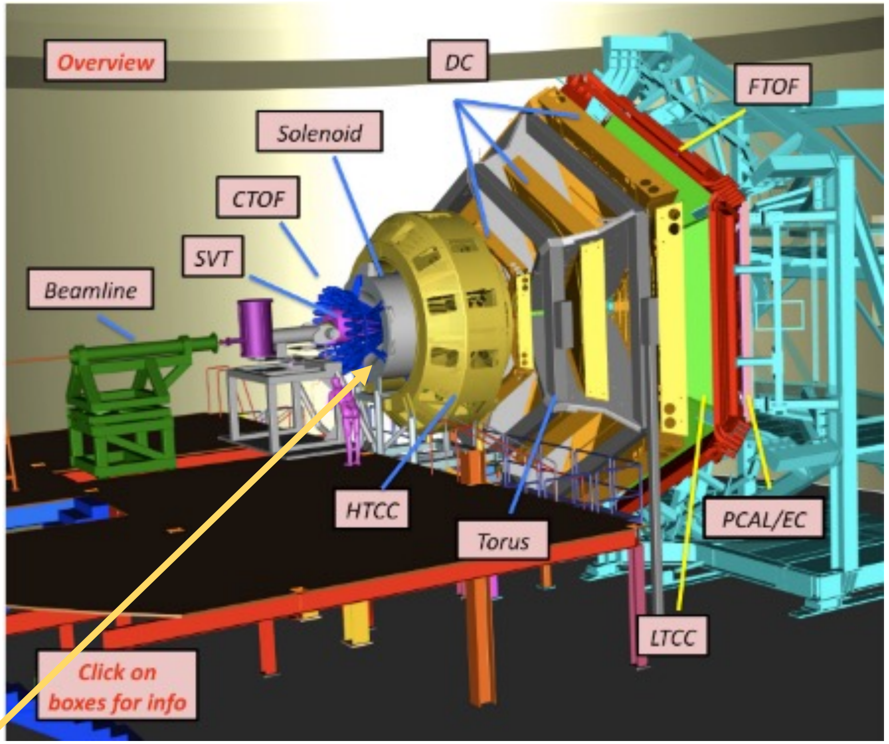
Selected Current and Recent Experiments: Micromegas

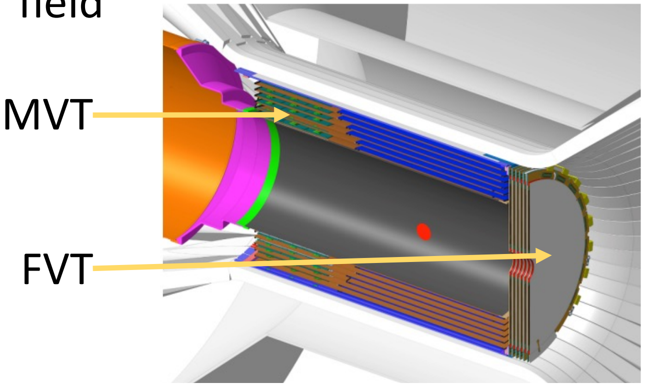
CLAS12 – Hall B

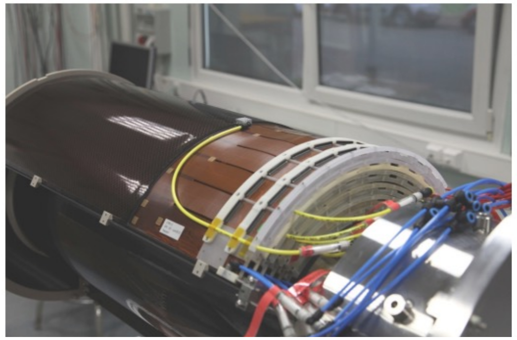
- 12 GeV upgrade of CEBAF Large Accelerator Spectrometer (CLAS) from 6 GeV era
- Default baseline detector for Hall B
- Contains solenoid (5T) and toroidal (3.6T) magnets
- Upgrade includes 6 Micromegas barrel layers and 6 forward Micromegas disks inside 5T magnet

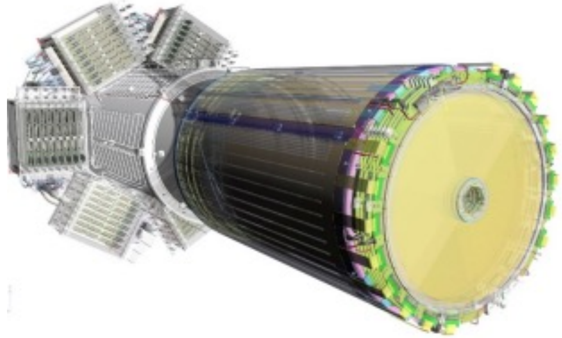


CLAS12 MVT and MBT

- MVT consists of 6 curved Micromegas layers complimenting Si vertex layers
- FVT is made up of 6 forward Micromegas disks
- All within 5T field







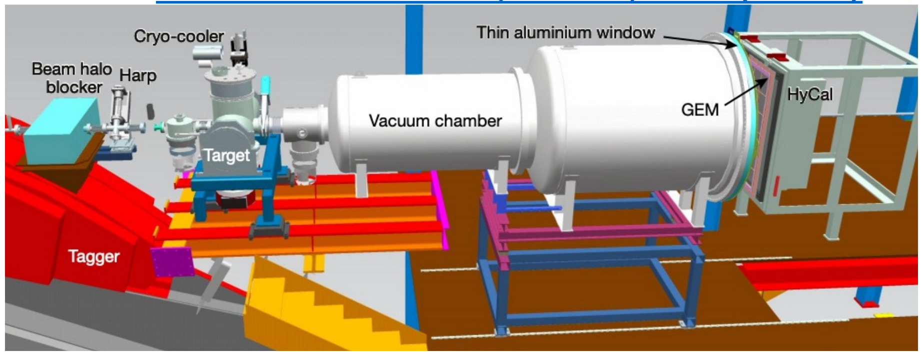
CLAS12: NIM A957, 163423 (2020)

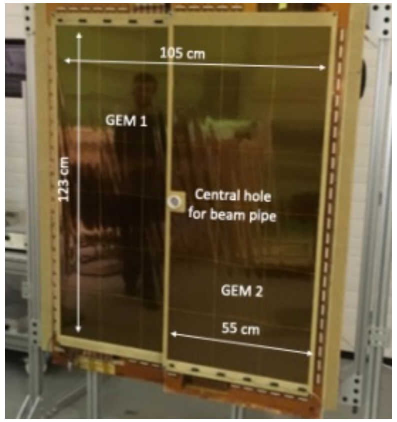
Selected Current and Recent Experiments: GEMs

Proton RADius Experiment (PRad) – Hall B

- Measure proton charge radius
- Large area triple-GEM used to improve HyCal performance

PRad: Nature 575, 7781, 147 (2019)

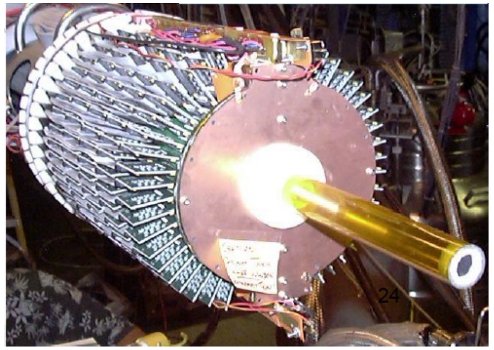


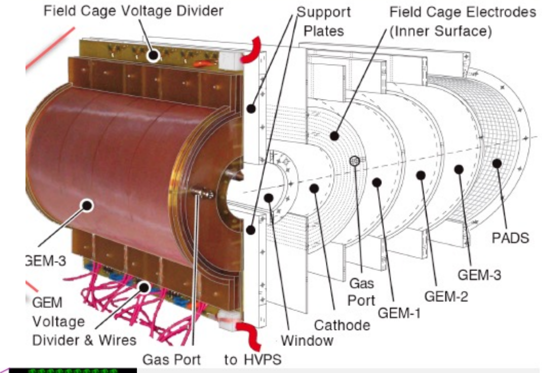


BoNuS and BoNuS12 (3rd gen.) – Hall B (CLAS12)

- Measure neutron F_2 structure function over large x range (~0.1-0.8)
- Radial TPC with 40 mm drift volume using Triple-GEMs detects low energy recoils
- Provides tracking and PID
- Sits around beampipe where SVT is located

BoNuS: NIM A592, 273 (2018)

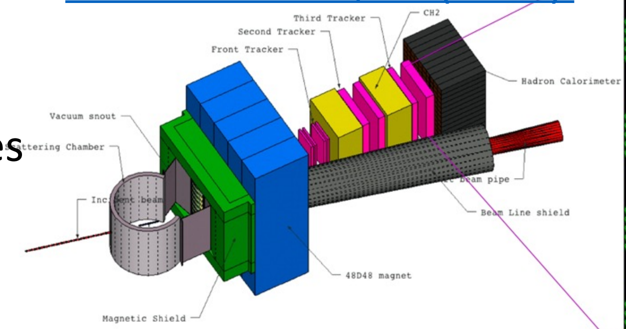


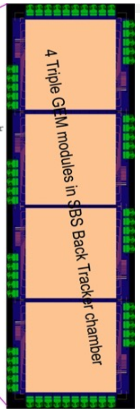


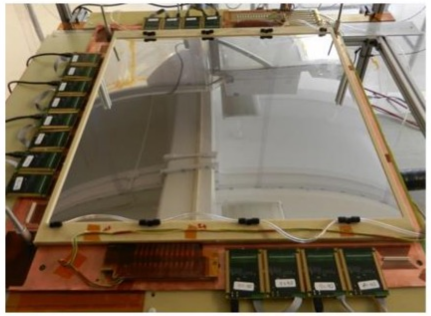
Super BigBite Specrometer (SBS) – Hall A

- Study nucleon structure (FF, TMD, GPD)
- Large triple-GEM trackers (40 x 50) and (50 x 60) modules
- Background rates ~400 kHz/cm2
- 70 um spatial resolution

SBS: NIM A782, 77 (2015)



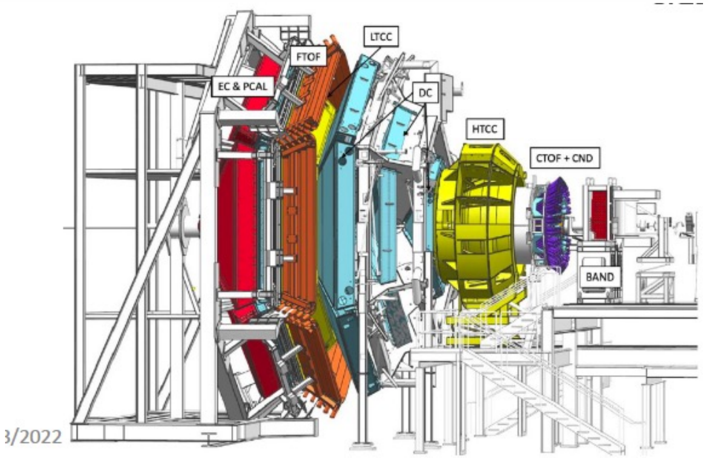


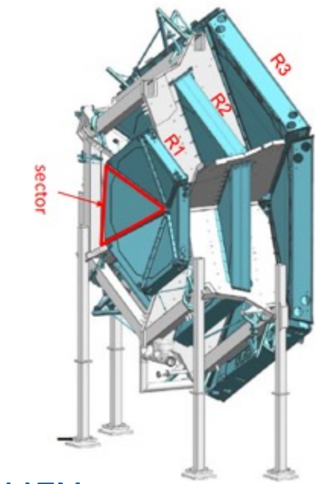


Selected Future Experiments

Hall B: CLAS12

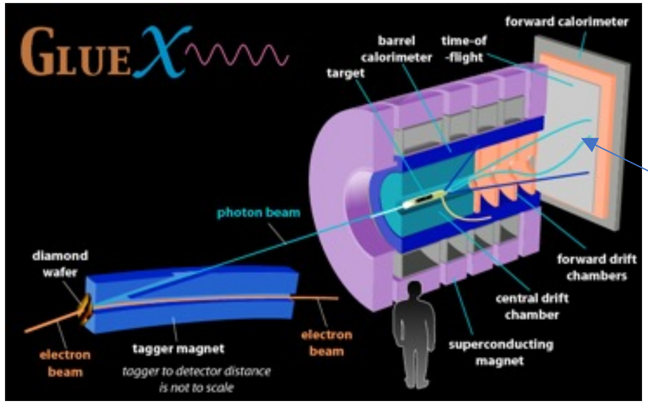
- Upgrade phase 1: double luminosity
  - Requires addition fast tracking precision layer in forward region to compensate for drift chamber limitation
- Upgrade phase 2: increase luminosity by 10x
  - Adding several layers to forward trackers / or replacing drift chambers by fast trackers
- MPGDs, such as μRWELLs are a great candidate



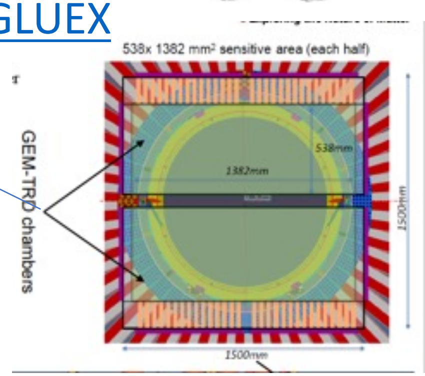


Hall D: GEM-TRD

- Could benefit from additional e/π separation
  - GEM based transition radiation detector could provide additional PID to compliment DIRC calorimeter e/π seperation
- More details on CLAS12 and GLUEX upgrades are discussed at [RD51 Collab. Meeting 2022, K. Gnanvo]



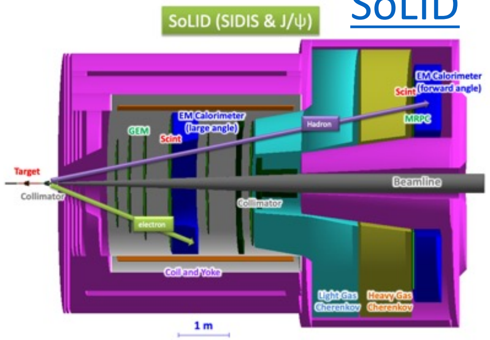
GLUEX



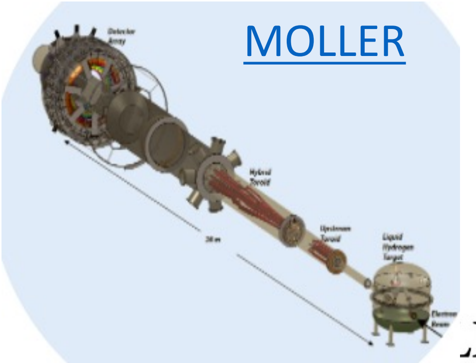
Hall A

- Future experiments in Hall A: SOlenoidal Large Intensity Detector (SoLID) and Measurement Of Lepton-Lepton Electroweak Reaction (MOLLER) experiments envision the use of MPGDs

SoLID



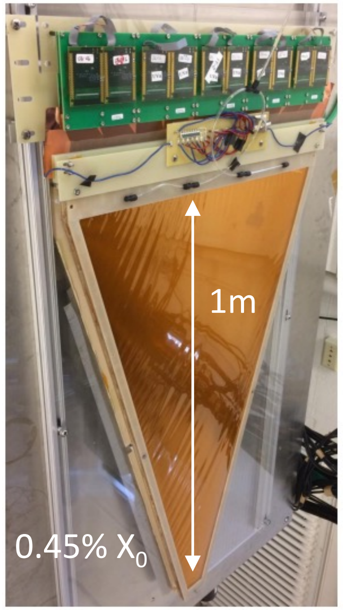
MOLLER



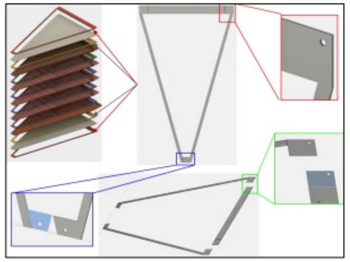
Needed MPGD Development

Development of large area and low mass MPGD structures

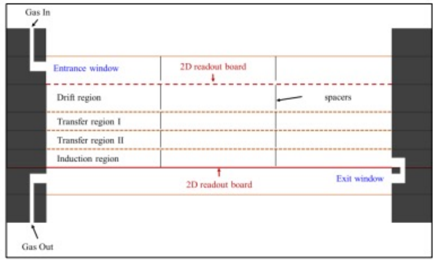
- Major requirement for MPGDs in NP is on low mass detectors (~1% X_0) to minimize
  - Multiple Coulomb scattering for momentum resolution
  - Background rates (low energy photon conversions)
- High luminosity CLAS12 μRWELL forward trackers will aim for 0.4% X_0
- Meter long *Only-foils* triple-GEM detectors, consisting of only GEMs, cathode, and readout foils and thin spacers in the active area, and have been built and tested with 0.45% X_0



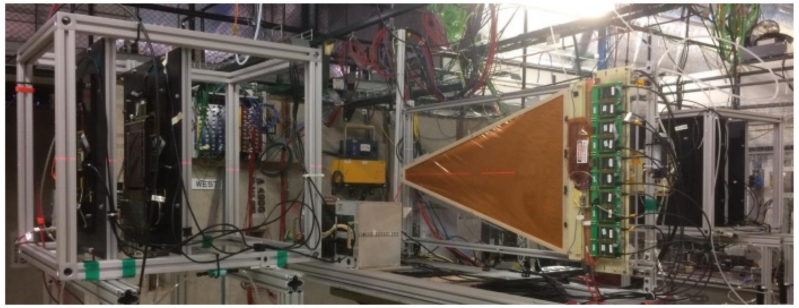
Low mass GEM prototype



3D view of low mass GEM



Cross section view of low mass GEM



Low mass GEM prototype in beam test at Fermilab (June - July 2018)

Additional Considerations

- At the level of 0.5%, the Cu electrodes of MPGD and mesh of Micromegas become significant.
  - Replace Cu in some areas by lighter metal (e.g. Al) or thin Chromium layers
- Not only material in detector active area needs to be considered, but all material in the active tracking volume (e.g. its support structures)
  - Investigate carbon fiber structures or narrow ceramic-based frames to replace standard fiber glass supports (G10/FR4)

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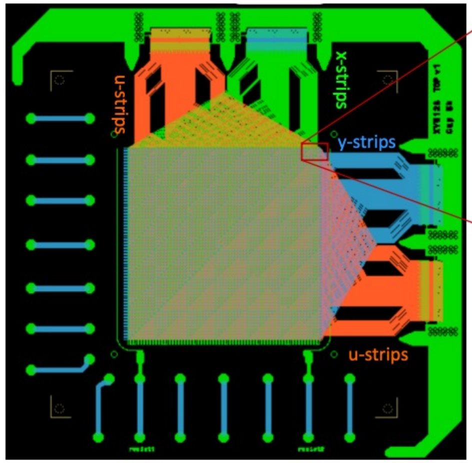
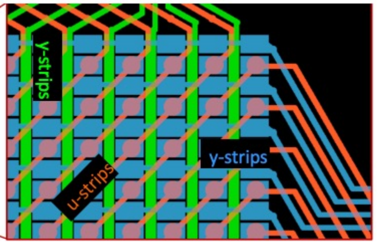
Needed MPGD Development

Development of 3-coordinate strip readout structures for MPGDs

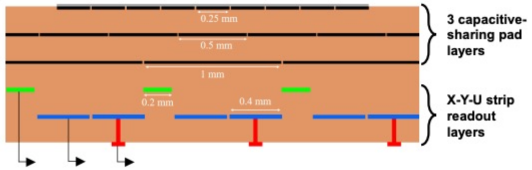
- Operating large-area MPGD detectors in high-rate environments leads to pile-up and multiple hits ambiguity issues.
- The issue is amplified by low-channel readout structures which use large pitches.
- 3-coordinate strip readouts could address this issue.
- When combined with fast electronics, they could allow for good timing, position and charge relation from the signal on the set of 3 strips to accurately reconstruct the position information with high precision.



Gerber view of 3-coordinates X-Y-U strips capacitive-sharing readout PCB



Zoomed view of X-Y-U strips design



Cross section view of 3-coordinates X-Y-U strips capacitive-sharing readout

High-rate resistive MPGDs

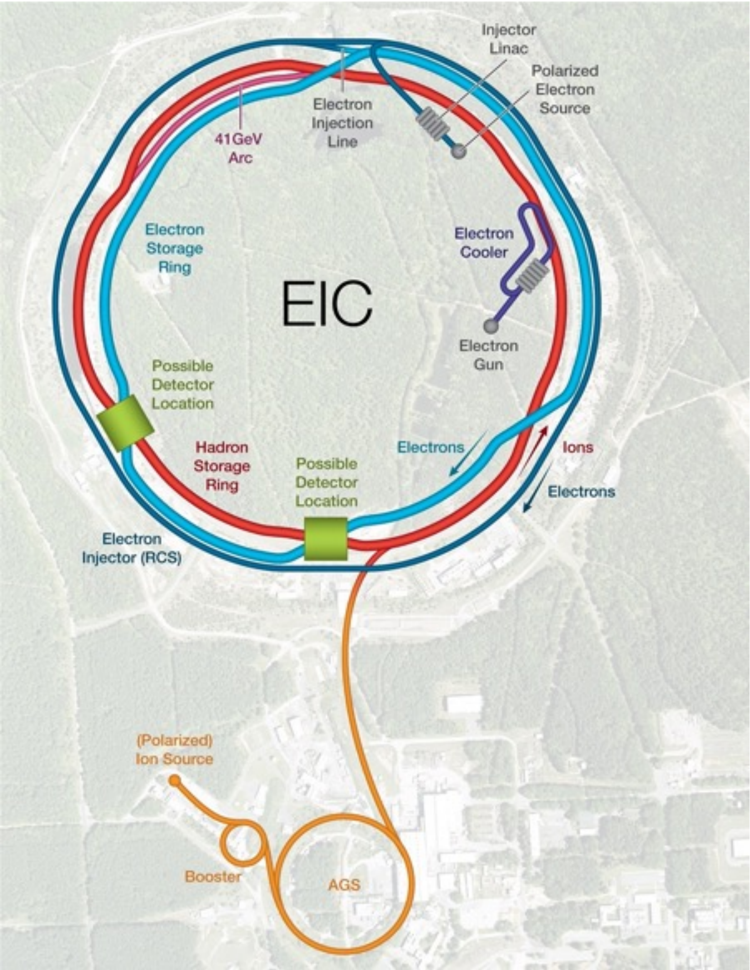
- Resistive MPGDs (resistive Micromegas and *μRWELL)* use thin resistive layers to quench energy from a spark discharge and reduce sparking rate significantly.
- Evacuation to the ground of the MPGD amplification charges through the resistive layer severely reduces the MPGD rate capability
- Large-area high-rate (~ MHz/cm^2) and radiation hard resistive MPGDs are critical for tracking in JLab's high-rate environment experimental halls

About the Electron-Ion Collider (EIC)

Slide adapted from RHIC AGS User Meeting 2022, Elke Aschenauer and Rolf Ent

Electron-Ion Collider (EIC)

- High Luminosity: L= 10^{33} – 10^{34} cm^{-2}sec^{-1}, 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: E_{cm} = 29 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Accommodate a Second Interaction Region (IR)
- EIC Users Group: ~1,300 users, 266 institutions, 36 countries



EIC Environment

- Low multiplicity per event: < 10 tracks
- Interaction rate of 500 kHz → non-significant pileup from collisions
- Radiation environment much less harsh than LHC → ~100x less

p/A beam → ← e beam

p: 41 GeV, 100 to 275 GeV

e: 5 GeV to 18 GeV

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EIC Physics and Requirements

Slide from RHIC User Meeting

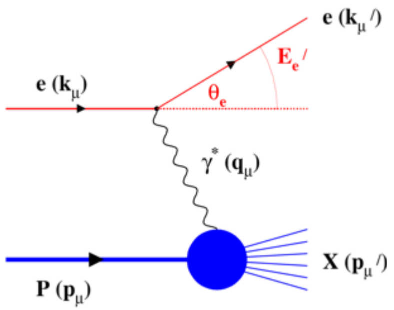
Parton Distributions in nucleons and nuclei

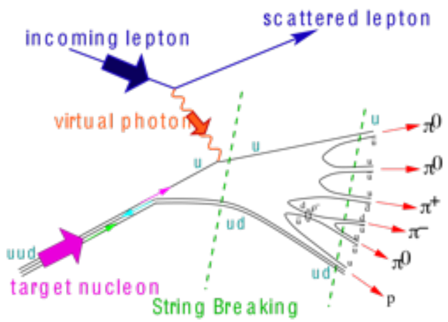
Spin and Flavor structure of nucleons and nuclei

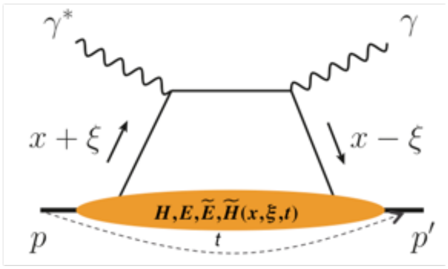
Tomography Transverse Momentum Dist.

QCD at Extreme Parton Densities - Saturation

Tomography Spatial Imaging







inclusive DIS

- measure scattered lepton
- multi-dimensional binning: x, Q^2

→ reach to lowest x, Q^2 impacts Interaction Region design

semi-inclusive DIS

- measure scattered lepton and hadrons in coincidence
- multi-dimensional binning: x, Q^2, z, p_T, Θ

→ particle identification over entire region is critical

exclusive processes

- measure all particles in event
- multi-dimensional binning: x, Q^2, t, Θ
- proton p_t: 0.2 - 1.3 GeV

→ cannot be detected in main detector

→ strong impact on Interaction Region design

$\int Ldt$: 1 fb^{-1} 10 fb^{-1} 10 - 100 fb^{-1}

machine & detector requirements

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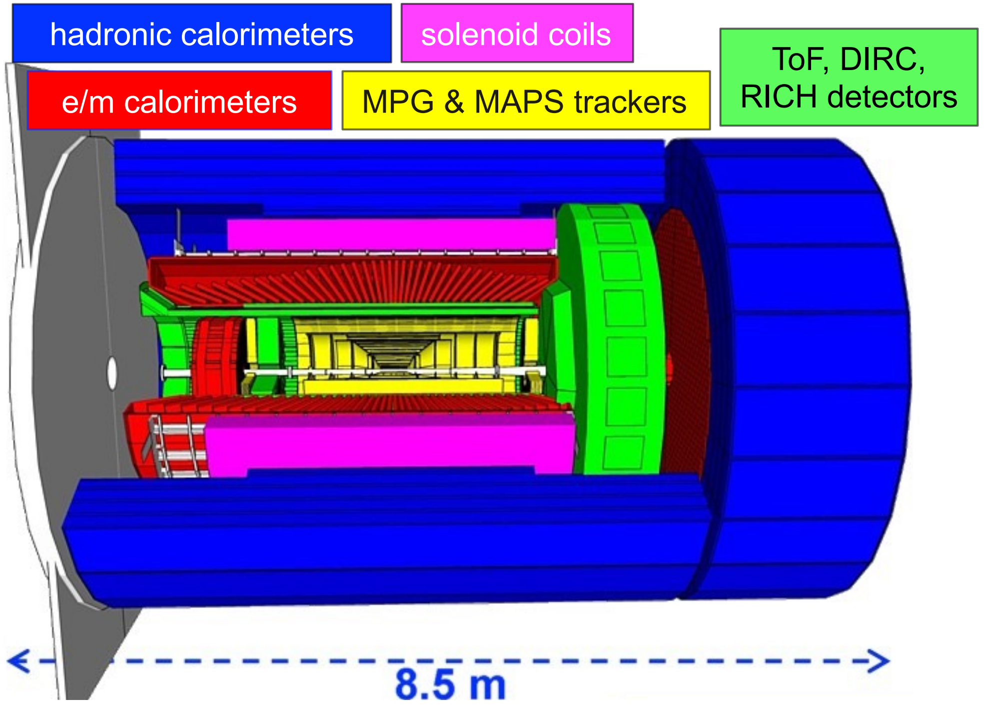
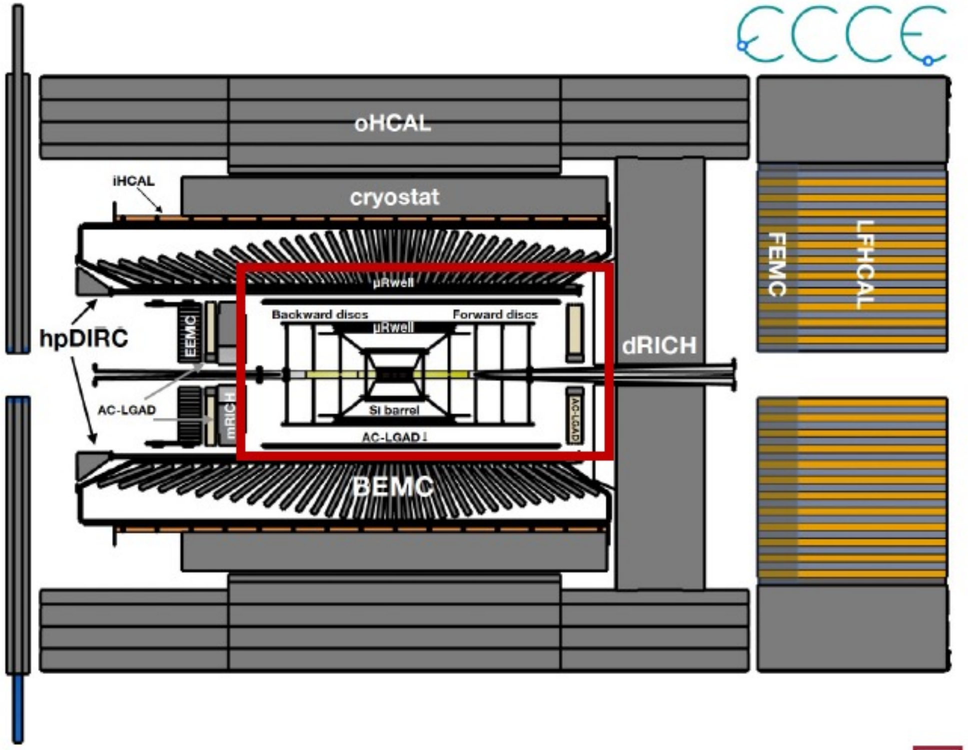
EIC Reference Detector

- The ATENA, ECCE, and CORE consortia (proto-collaborations) submitted detector proposals for the EIC reference detector design selection.
- The ECCE detector, which will reuse the 1.5 T Babar magnet, has been selected as the EIC reference detector design
- The EIC detector 1 proto-collaboration has been formed to proceed with the technical design for the EIC project detector with optimizations based on the ATHENA and ECCE detector designs.



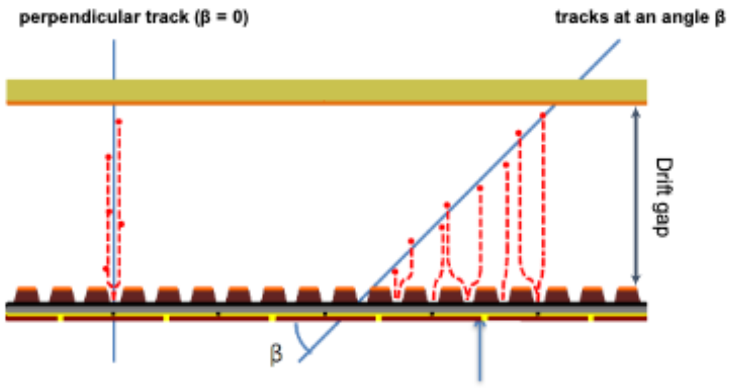


Needed MPGD Development

MPGDs at the EIC

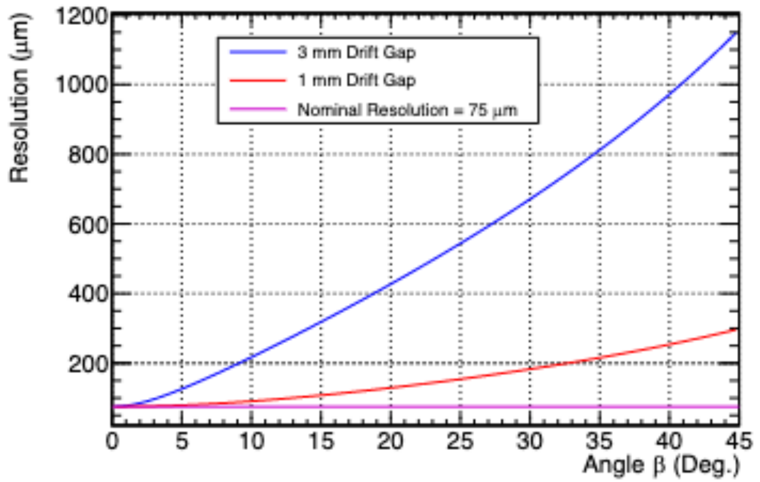
- MPGDs, such as Micromegas and μRWELL, are well suited to meet the EIC's tracking requirements:
  - Large acceptance, Low material budget, and provide excellent momentum resolution
- MPGD-TRD could provide additional e/π separation in the hadron-going direction
- With PID critical to the EIC physics program, MPGD-based photon detectors would fit in perfectly

μRWELL cross section



MPGD R&D for the EIC

- EIC MPGD R&D has benefited greatly from the long running R&D program through BNL in association with JLab and DOE Office of Nuclear Physics
- Much of the critical EIC R&D overlaps with the R&D interests of Jlab
  - Large-area and low-mass detectors, precise spatial resolution, low-channel count readout, resolving track ambiguities, and PID capable MPGDs
- Critical for EIC tracking to provide precision spatial resolution over large angular acceptance (~+/-30°)
  - Investigating thin gap (~< 1mm) Micromegas, μRWELL, and hybrid-MPGD (GEM+μRWELL)

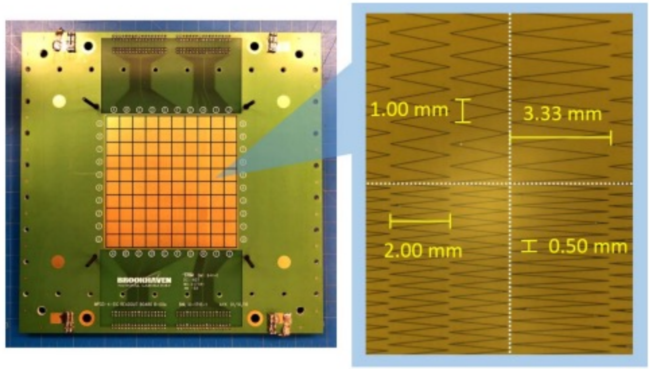


Needed MPGD Development

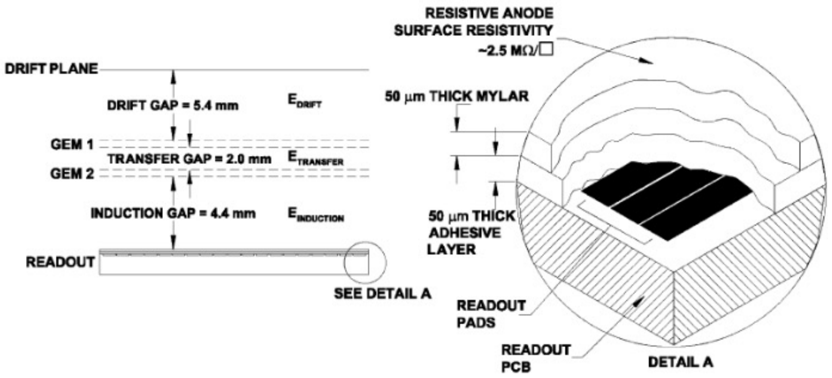
Low channel count readout structures

- Precision large-area detectors typically require fine pitch readout structures leading to many channels needing to be readout → drives up cost
- 3 potential low channel count readout solutions
  - **Zigzag readout**: Interleaves of zigzag facilitate charge sharing between wide adjacent strips
  - **Resistive readout**: Surface resistivity of resistive layers could enhance lateral spread of amplification charge cloud between large pitch strips/pads
  - **Capacitive-sharing readout**: Capacitive coupling between stack of pad layers to transfer charges to large pitch strip/pad readout.

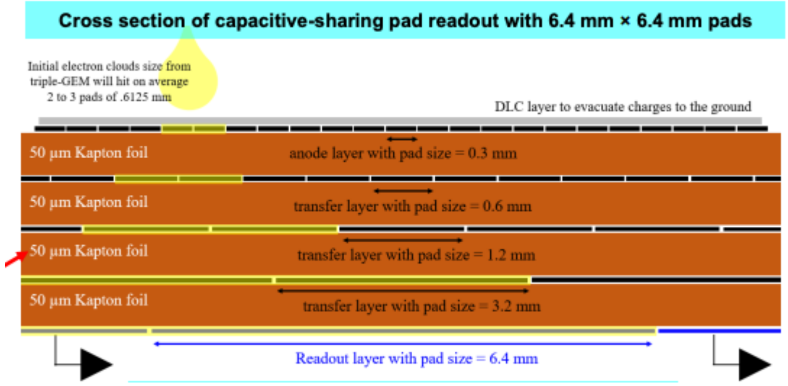
Zigzag readout: IEEE Trans. On Nucl. Phys. Sci, 1-1, 06 (2020)



Resistive readout: NIM A518, 721 (2004)



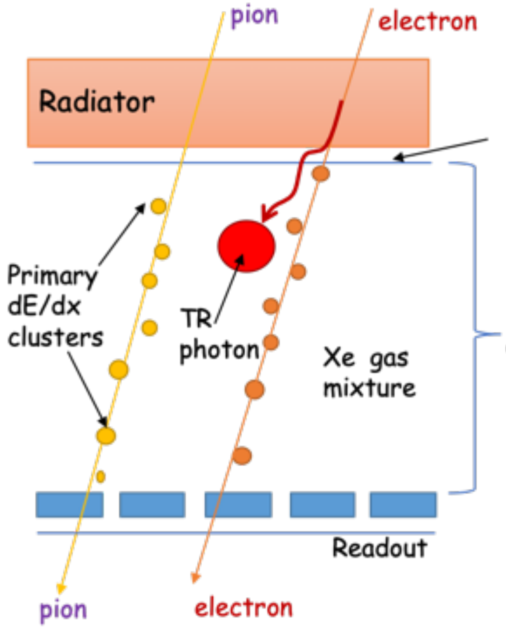
Capacitive-sharing: RD51 Collab. Meeting (2021), K. Gnanvo



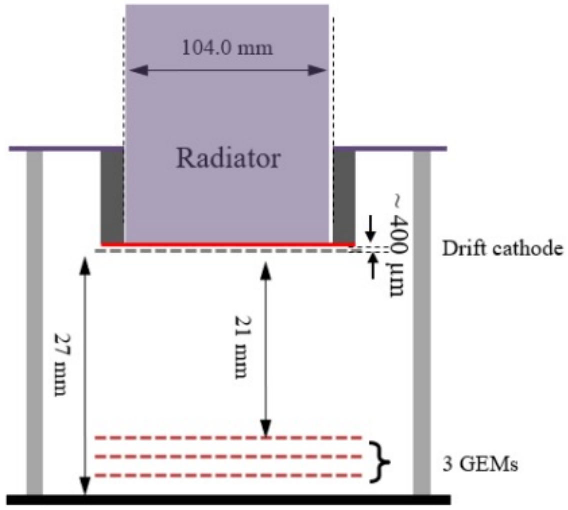
MPGD-Based Transition Radiation Detectors

MPGD-TRD

- Electron identification is critical to EIC physics program.
  - Secondary electrons that could be emitted from leptonic and semi-leptonic decays of hadrons
  - Relatively large QCD background from hadrons in hadron-direction
- MPGD-TRD could provided e/π separation as well as precision 3D tracking
- GEM-TRD was successfully built and tested and required
  - Heavy gas (Xe), large drift gap, and fast electronics (JLab Flash-ADC (FADC)



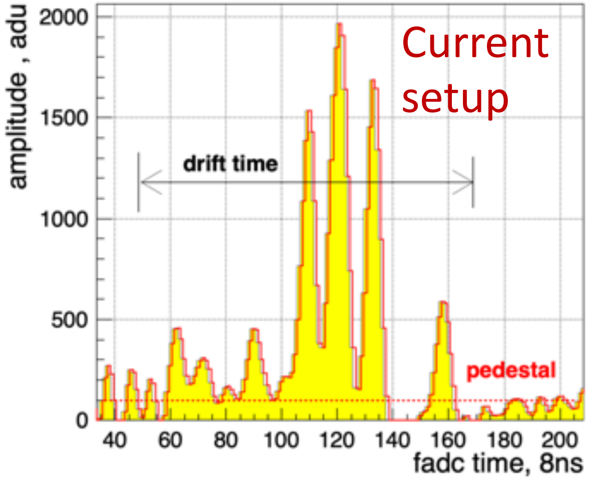
[GEM-TRD: NIM A942, 162356)](GEM-TRD: NIM A942, 162356))



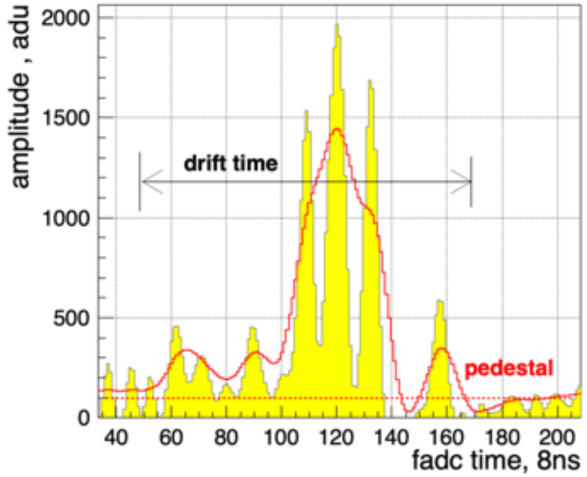
R&D

- Develop large scale prototype
- Investigate other MPGD technologies (Micromegas, μRWELL)
- Develop dedicated electronics
  - GEM-TRD protype used FADC (125 MHz, 12 bit) with GAS-II pre-amp ASIC chips for 2.6 mV/fC amplification with 10 ns peaking time
  - Streaming readout capable (FADC is trigger based)

~ 20ns shaping time



80ns (Sampa) shaping time



MPGD-Based Photon Detectors in RICH Technologies

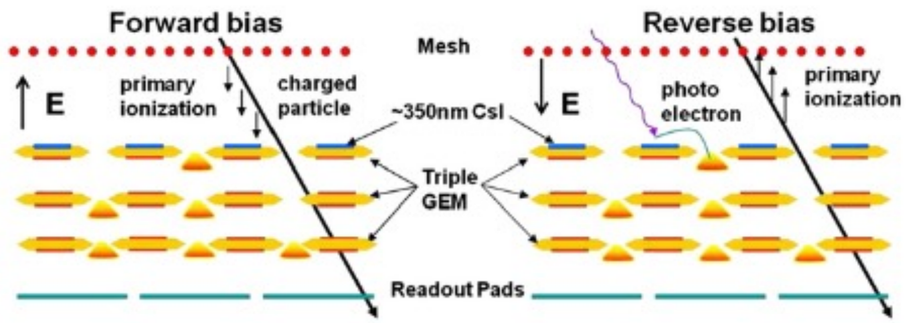
MPGD-Based Photon Detectors

- Have been and continue to play a major role in establishing and operating Ring Imaging Cherenkov (RICH) counters
  - Cover large areas
  - Have minimum material budget → critical when in experiment acceptance
  - Can operate in magnetic fields
- Two critical areas of gaseous photon detectors
  - **Selection of the photoconverter**: Only CsI (high work function) has been reliably used
  - **Photoelectron extraction**: extracted photoelectrons can be back scattered by gas molecules and reabsorbed in the photoconverter. Effective extraction requires specific gas and high E-fields.
- MPGDs offer natural answers to ion-back flow and photon feedback suppression.

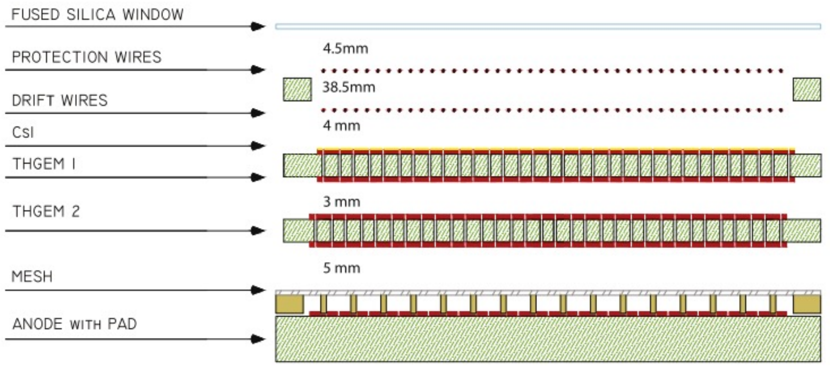
R&D Areas

- Development of compact RICH for PID of high momentum particles
- Find alternative to FluoroCarbon gases → Pressurized (few bar) noble gas volume
- Possibility to identify novel solid-state photoconverters with higher QE

PHENIX HBD (RHIC): NIM A646, 35 (2011)

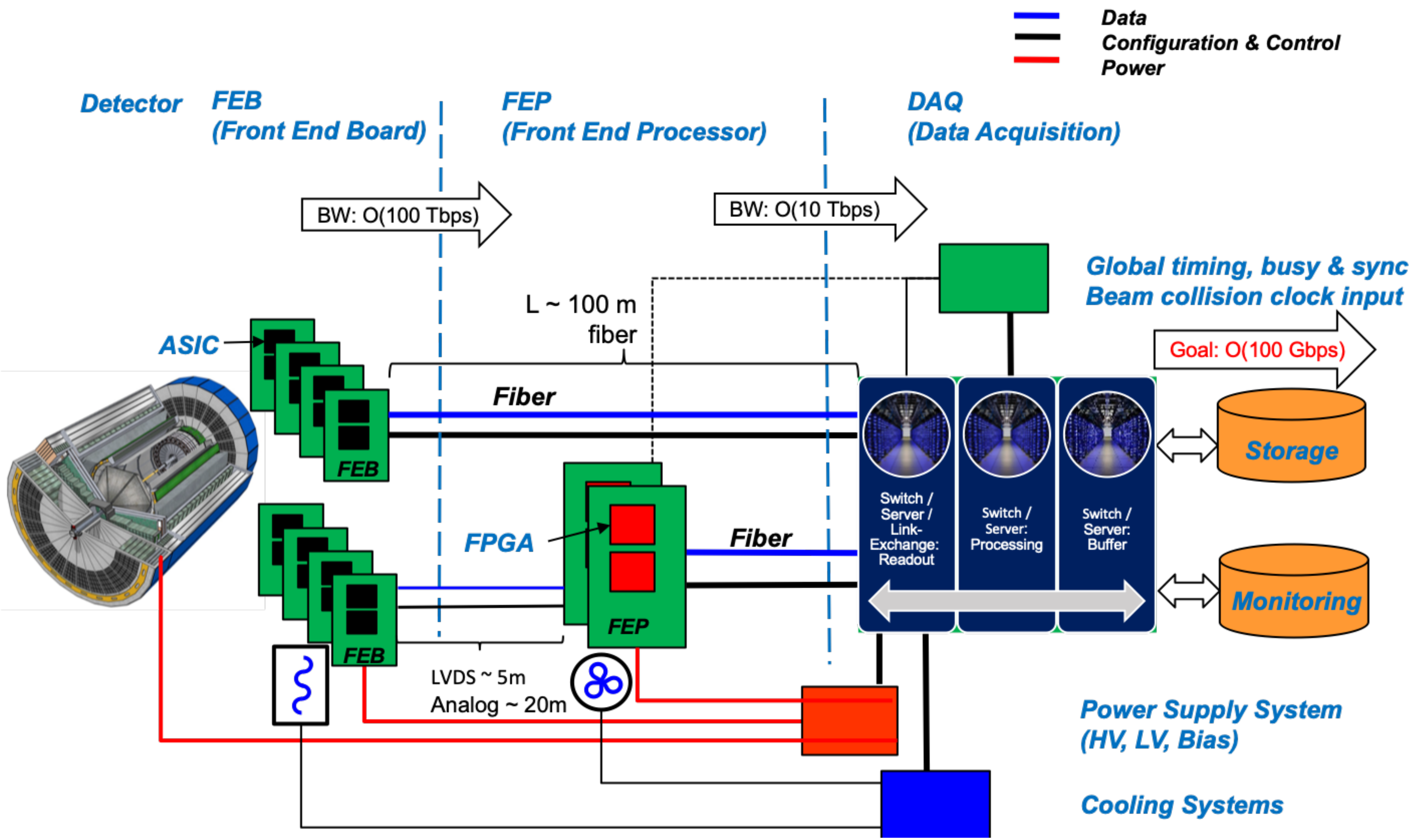


COMPASS RICH upgrade: NIM A936, 416 (2019)



Electronics and Readout: EIC Streaming Readout

[Slide from RHIC User Meeting](#)



No trigger → much more flexibility to do physics not planned from the start

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Electronics and Readout: The ASICS

Current Streaming Capable ASICs

- There are only a few front-end ASICs compatible with a streaming readout DAQ. Among them
- SAMPA chip
  - Developed by Sao Paulo University
  - 32-channel ASIC with on-board pre-amp, pulse shaping, digitization and DSP subsections.
  - To be used in sPHENIX experiment's TPC at RHIC
- VMM chip
  - Developed by BNL for Micromegas and sTGC detector of ATLAS Muon Spectrometer’s New Small Wheel upgrade.
  - 64-channel mixed signal ASIC based on IBM 130 nm technology.
  - Used in STAR experiment’s sTGC at RHIC

The SALSA ASIC

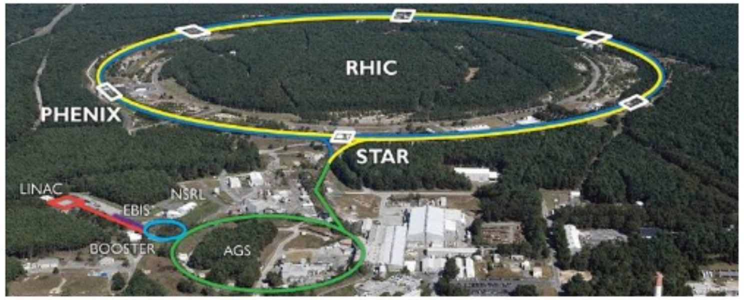
Parameter	Value
Analog characteristics	
Number of channels	64
Peaking time range	50 to 500 ns
Input dynamic range	0-50 fC to 0-5 pC
Input capacitance range	Optimized for 200 pF, reasonable gain up to 1 nF
Input rates	25 kHz/channel, with faster CSA reset for larger rates
Additional feature	Reversible polarity
Digital characteristics	
ADC sampling rate	10 to 50 MS/s
ADC dynamics	12 bits
Data processing	Pedestal subtraction, common mode correction, zero suppression, peak finding, software trigger generation
Output data links	One or a few gigabit links

Summary

- MPGDs have and continue to have a prominent role in many NP experiments
- New experiments (e.g. the EIC) and experiment upgrades envision MPGDs as having critical roles and is driving MPGD R&D within the NP community.
- R&D critical and mostly specific to NP centers around continuing to reduce detector material budget
- Other key areas which have a common interest in HEP include
  - Building large area detectors
  - Improving spatial resolution
  - High-rate capable
  - Fast timing
  - Reducing channel count
  - Developing PID capable MPGD based detectors

Continuous Electron Beam Accelerator Facility (CEBAF)

Facility for Rare Isotope Beams (FRIB)



Relativistic Heavy Ion Collider (RHIC)