Overview of Micro-Pattern Gas Detectors (MPGDs) & Applications

JLAB - HALL A COLLABORATION MEETING

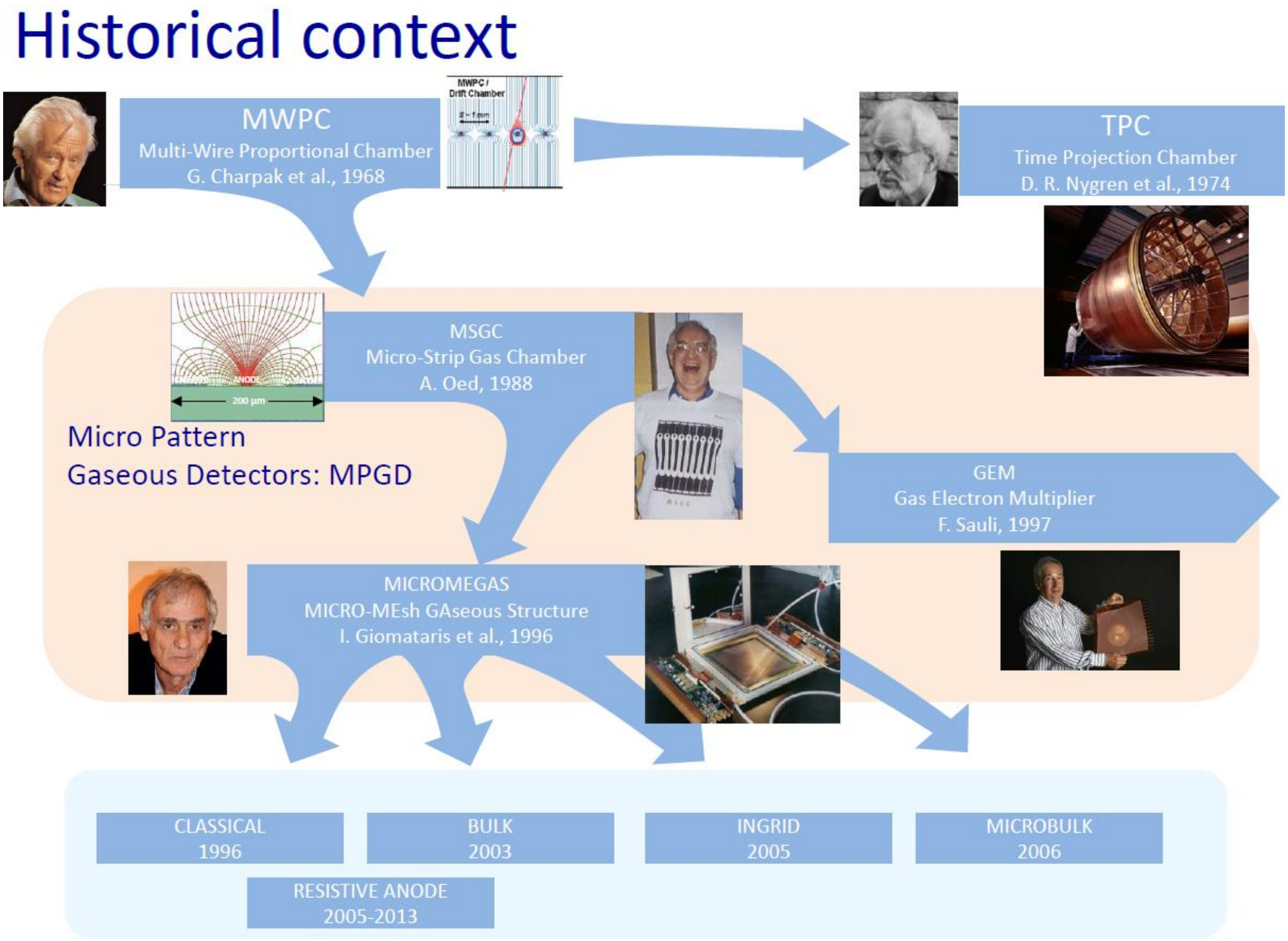
January 31, 2019

Kondo Gnanvo - University of Virginia

Outline

- Overview of Micro Pattern Gas Detectors (MPGDs) Technologies
- GEM Trackers for SBS, MOLLER, SoLID ….
- MPGDs elsewhere @ JLab
- MPGDs for the Electron Ion Collider (EIC)
- The RD51 Collaboration

From MWPCs to MPGDs



Historical context

MWPC
Multi-Wire Proportional Chamber
G. Charpak et al., 1968

TPC
Time Projection Chamber
D. R. Nygren et al., 1974

MSGC
Micro-Strip Gas Chamber
A. Oed, 1988

Micro Pattern
Gaseous Detectors: MPGD

GEM
Gas Electron Multiplier
F. Sauli, 1997

MICROMEGAS
MICRO-MEsh GAseous Structure
I. Giomataris et al., 1996

CLASSICAL
1996

BULK
2003

INGRID
2005

MICROBULK
2006

RESISTIVE ANODE
2005-2013

MPGDs:

Gas Electron Multipliers (GEMs)

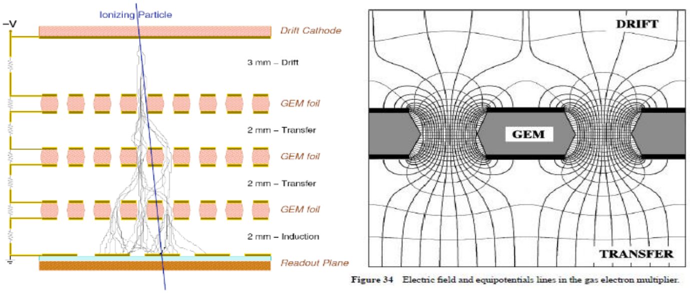
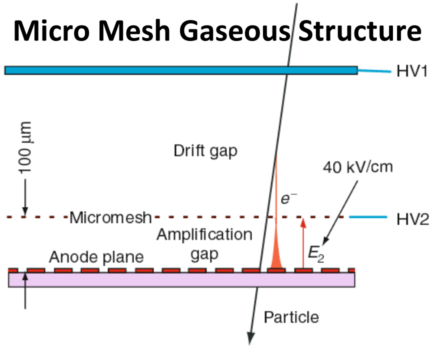


Figure 34 Electric field and equipotentials lines in the gas electron multiplier.

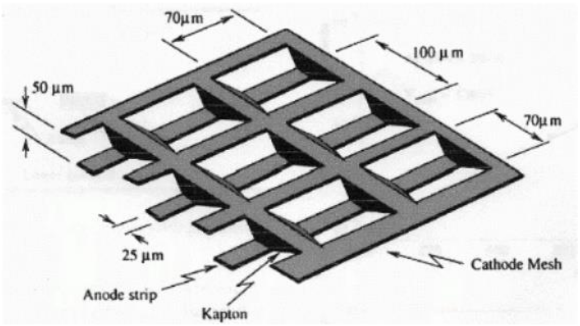
F. Sauli, Nucl. Instr. and Meth. A386(1997)531

Micro Mesh Gaseous Structure



Y. Giomataris, NIMA 419 (1998) 239

Micro Wire Chamber



B. Adeva et al., NIMA 435 (1999) 402

Micro Gap Chambers

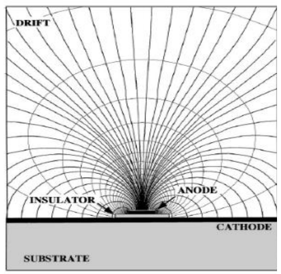


Figure 24 Equipotential and electric field lines for the microgap chamber.

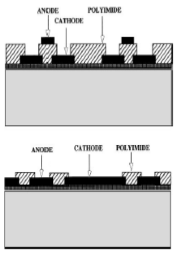
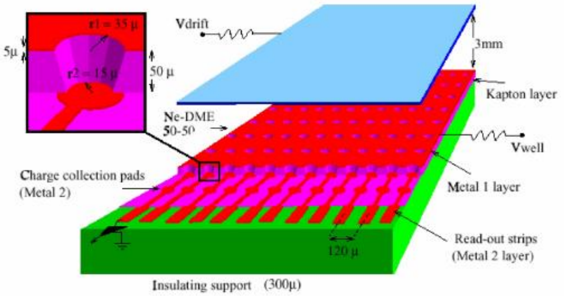


Figure 25 Two variants of small-gap chambers, using thick polyimide ridges to prevent the onset of discharges.

Angelini F., NIMA 335:69 (1993)

MicroWELL



R. Bellazzini, NIMA 423 (1999) 125

MicroDot

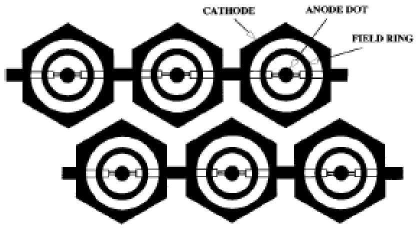
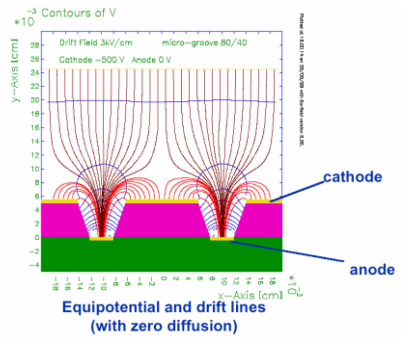


Figure 26 Schematics of the microdot chamber. A pattern of metallic anode dots surrounded by field and cathode electrodes is implemented on an insulating substrate, using microelectronics technology. Anodes are interconnected for readout.

Biagi SF, Jones TJ. NIM A361:72 (1995)

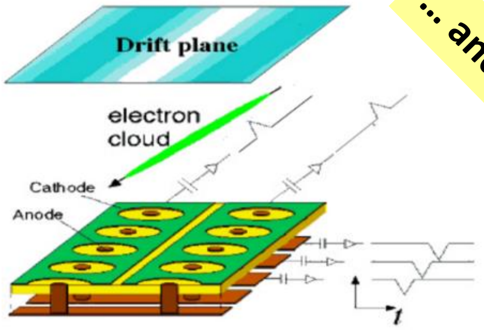
Micro Groove



Equipotential and drift lines (with zero diffusion)

R. Bellazzini , NIMA 424 (1999) 444

µ-PIC



Ochi et al NIMA 471 (2001) 264

… and so many others

Micro Gap Wire Chamber

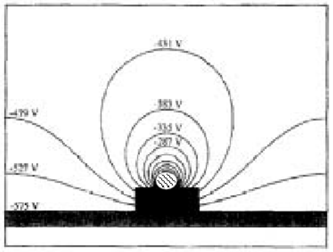


Figure 2.27 Scheme of a MGWC with equipotential and field lines. The circle filled with lines is the section of an anode wire [CHRISTOPHEL1997].

NIMA 398 (1997) 195

MSGC: Birth of Micro Pattern Gaseous Detectors (MPGDs)

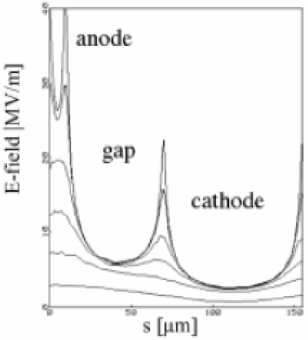
Solution to MWPC rate limitation:

⇨ Basic idea of Micro Pattern Gaseous Detectors (MPGDs) ⇨ Fast evacuation of the ions

⇨ Adopt Semiconductor industry technology**: Photolithography, Etching, Lift-off, Coating, Doping,**

⇨ **Micro Strip Gaseous Counter (MSGCs)** **[Oed (1988)]** :

- Cathode strips and anode strips on the same substrate
- pitch ~ 100 µm ⇨ Excellent spatial and high rate capability



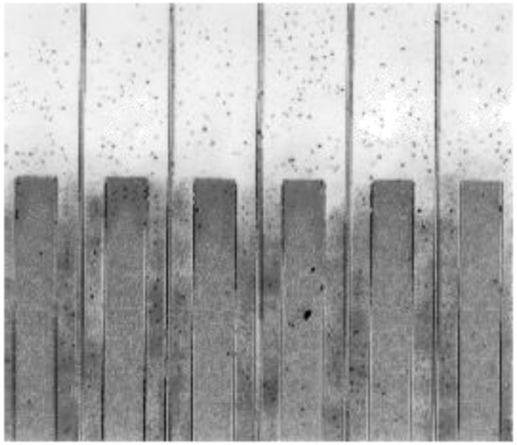


Figure 1 Close view of one of the first microstrip plates developed by Oed at the Institut Laue-Langevin. On an insulating substrate, thin metallic anode strips alternate with wider cathodes; the pitch is 200 μm.

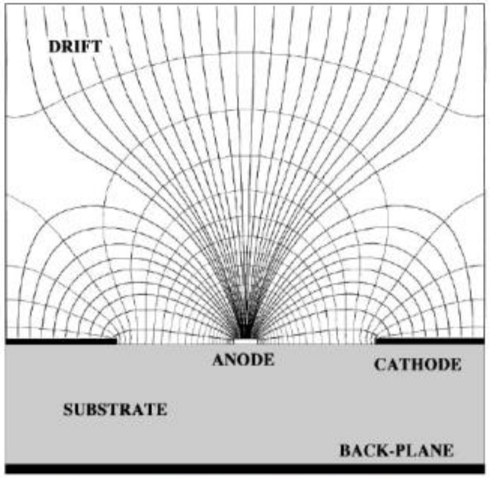
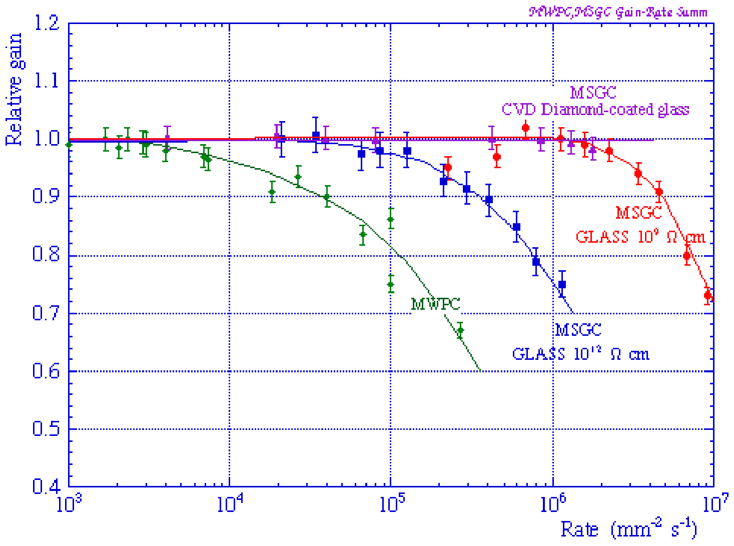


Figure 2 Equipotentials and field lines in the microstrip chamber, computed close to the substrate. The back-plane potential has been selected to prevent field lines entering the dielectric.

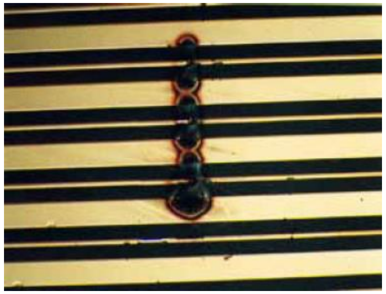


BUT: MSGCs suffer from long (even medium) term stability issues

⇨ High discharge rate and charging up of the substrate

- **Aging:** **fast deterioration due to sustained irradiation**

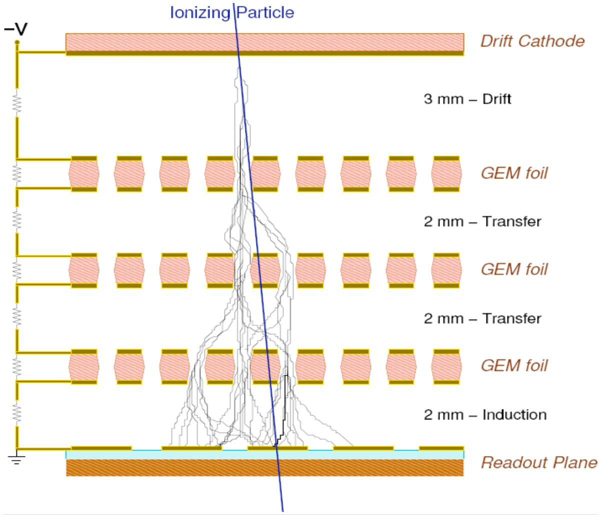
⇨ Substrate material, metal of the strips, type and purity of the gas mixture



High electric field in the region in between the amplification-stage-electrodes (from avalanche to discharge)

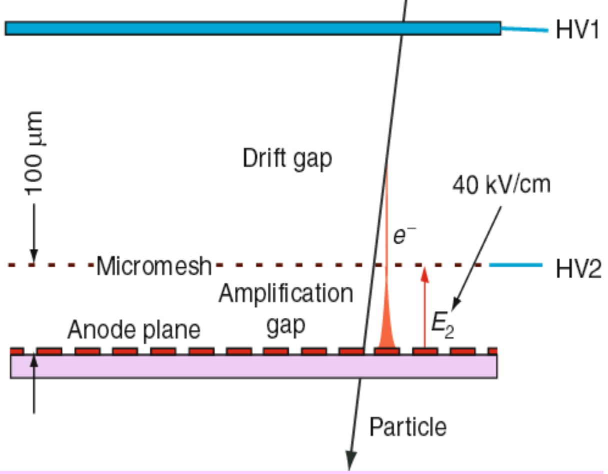
Mature MPGD technologies

GEM: Gas Electron Multipliers



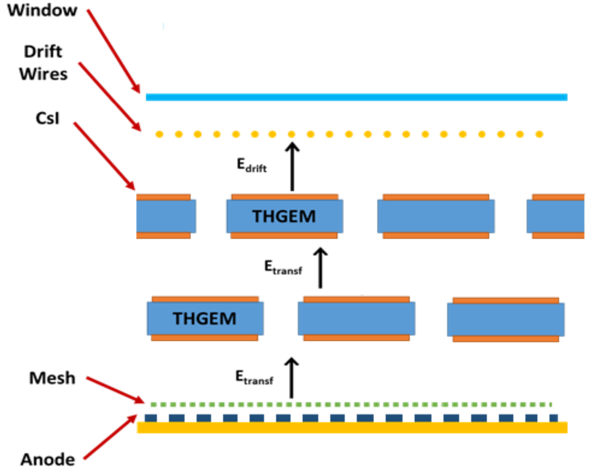
F. Sauli, Nucl. Instr. and Meth. A386 (1997) 531

Micromegas:
Micro Mesh Gaseous Structure



Giomataris, Nucl. Instr. and Meth. A419 (1998) 239

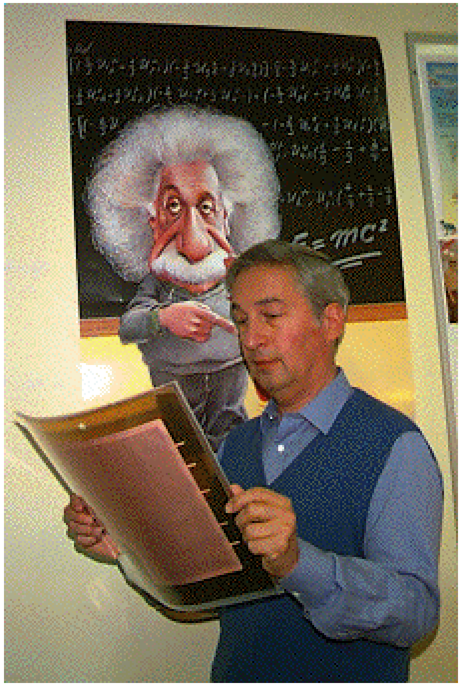
Thick GEM (THGEM)



R. Chechik, A. Breskin, C. Shalem

GEM Detectors

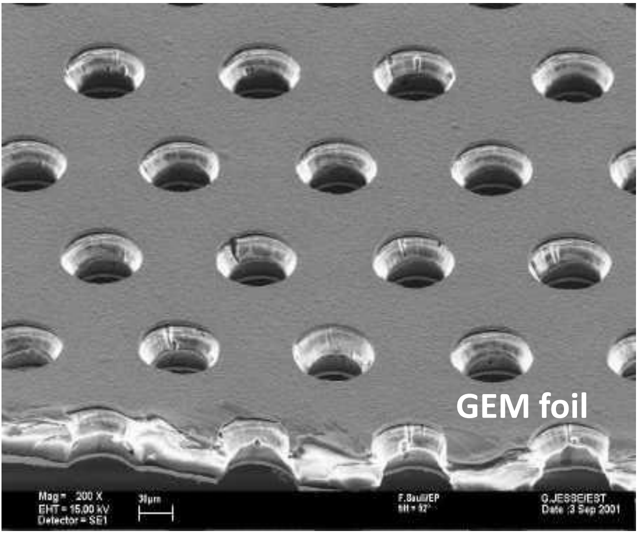
- GEMs are Micro Pattern Gaseous Detectors (MPGDs) invented at CERN in 1997 by Dr. Fabio Sauli
- Provides a cost effective solution for high resolution tracking in high rates and over large area
  - ✓ Rates capability exceed several MHz / cm^2
  - ✓ Spatial resolution better than 70 µm are easily achievable
  - ✓ Single mask GEMs ⇨ Large area capability (~1 m^2)
  - ✓ Ability to cover large (10s to 100s of m^2) area at low cost
  - ✓ Low material budget (~ 0.5 % radiation length)
  - ✓ Robust technology: Resists aging and Radiation hardness
- Already used in HEP and NP experiments around the world: COMPASS, BoNuS, KLOE, PRad, TOTEM, STAR FGT, PHENIX HBD,
- Adopted for many future experiments: CMS upgrade, ALICE TPC, SBS, SoLID, EIC Trackers etc …

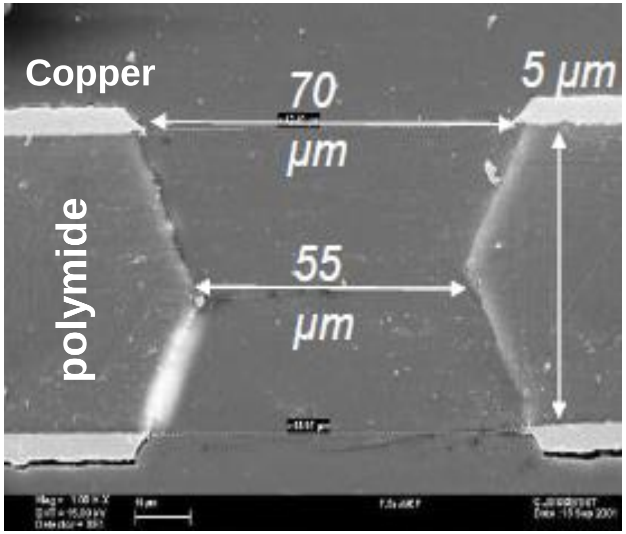


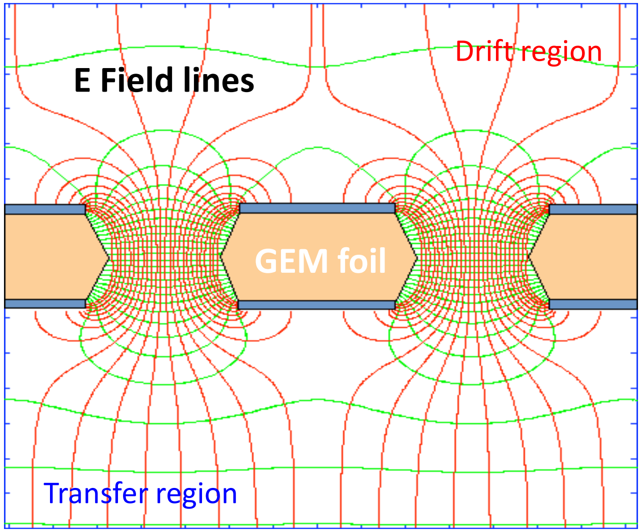
F. Sauli, Nucl. Instr. and Meth. A386 (1997) 531

GEM Detectors

- Thin, metal-clad polymer foil chemically perforated by high density of holes, (typically 100 holes /mm^2)
- Voltage of ~ 350 V across the Cu electrode creates a strong field in the hole leading to amplification
- The ionization pattern is preserved by design with the electric field focusing the charges inside the holes





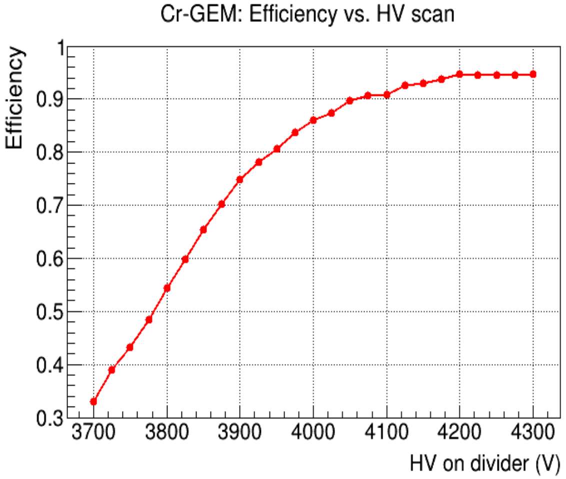


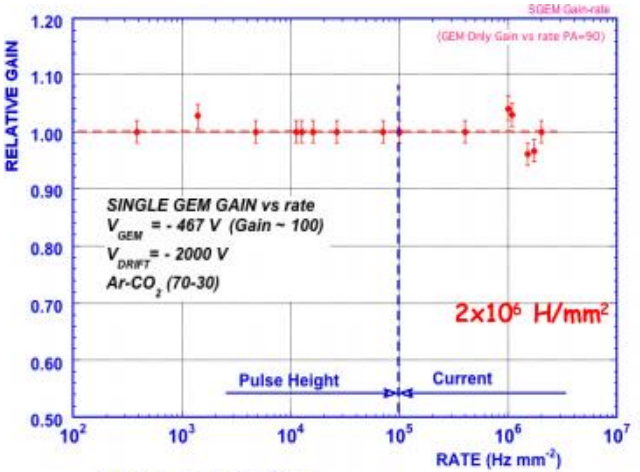
UNIQUE FEATURE

Charge amplification is decoupled from the charge collection ➩ *Multi-stage amplification*

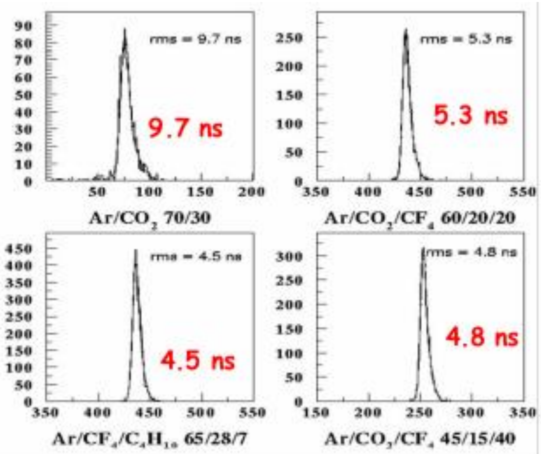
F. Sauli, Nucl. Instr. and Meth. A386 (1997) 531

GEM Detectors

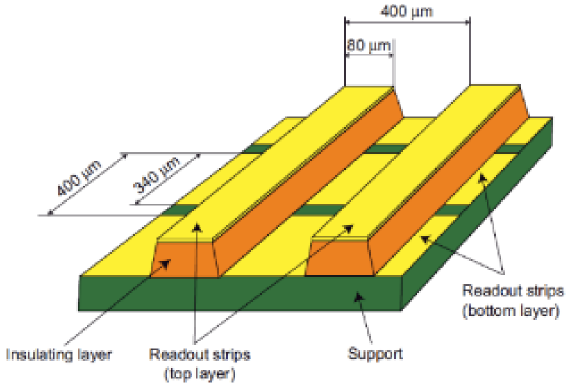


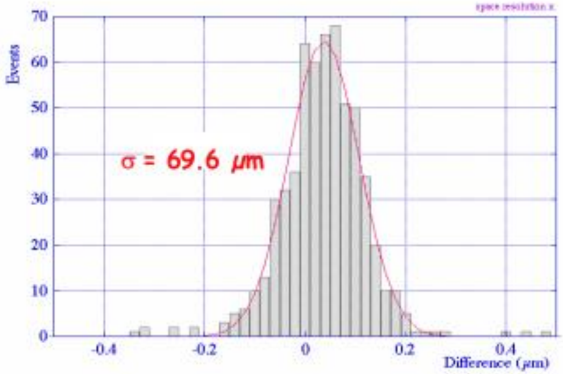


Rate capability

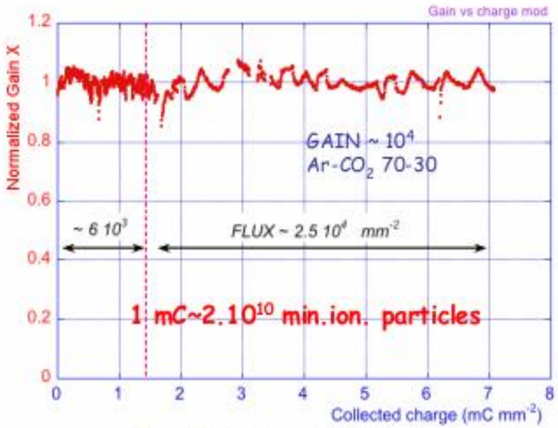


Time resolution





Space resolution



Ageing properties

Breakthrough with GEM Detectors

Single Mask Techniques for large GEM foils production

- ⇨ Allow for the production of large GEM foils (> 50 cm x 50 cm)
- ⇨ Require single photo lithography mask on one side of the GEM foil during the different etching processes
- ⇨ Big step forward for current and future GEM project like CMS Muon detector upgrade, SBS and SoLID @ JLab, Muon Chamber for PANDA @ FAIR

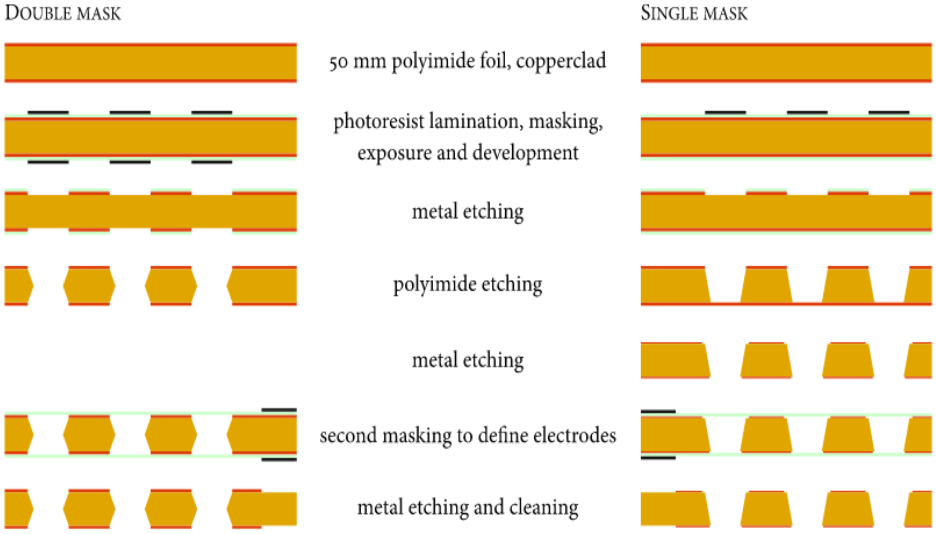


Figure 1. Schematic comparison of procedures for fabrication of a double-mask GEM (left) and a single-mask GEM (right).

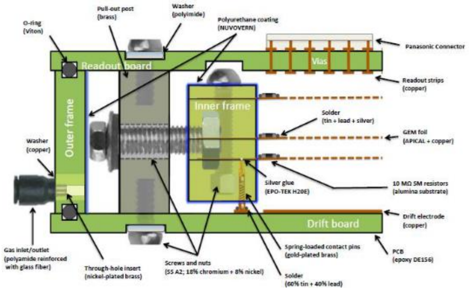
Limitation from mask alignment
⇨ max active area ~ 40×40 cm ^{2}

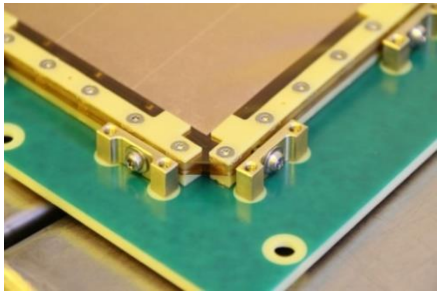
No alignment required
⇨ Very large GEM foil

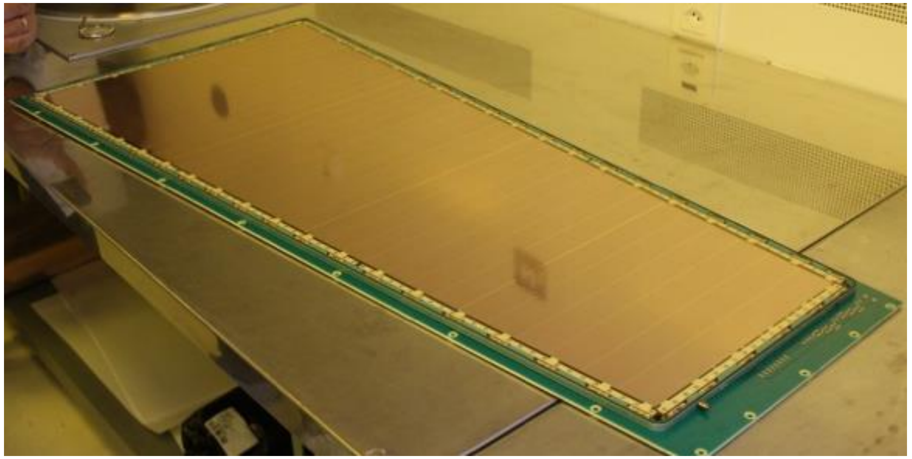
Progress on large area GEMs Serge Duarte Pinto et al., Jinst, November 26, 2009 [http://arxiv.org/pdf/0909.5039v2.pdf]

NS2 Triple GEM assembly technique

- ⇨ Mechanical stretching with small frames with the use of a set of screws, fittings for the stretching
  - ❖ Control of the stretching and the flatness of the GEMs
  - ❖ No glue involved: Chamber can be re-opened
  - ❖ No need for spacers in active area
- ⇨ **BUT: Lots of screws and rigid supports to hold tension**







pioneered by CMS GEM Muon Upgrade collaboration & RD51 Cool Rui De Oliveira, CERN PCB workshop

Micromegas: Small gap parallel plate detector

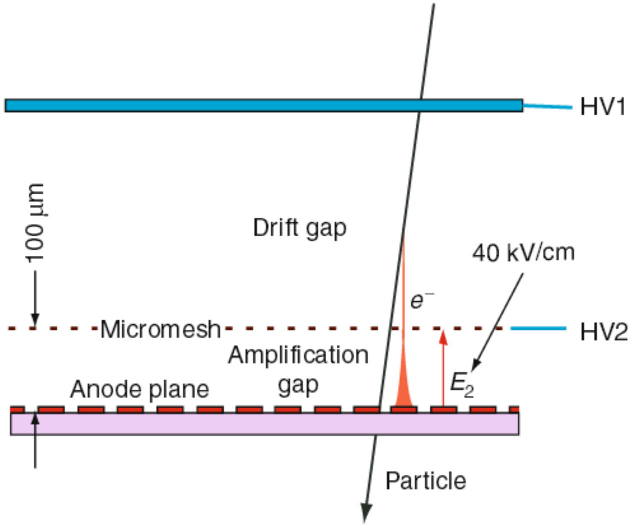
Two-stage parallel-plate avalanche chamber of small amplification gap:

Amplification in the ~100 μm gap between the mesh electrode and the anode

Small gap, high field:

- ⇨ fast movement of positive ions that are mostly collected on the mesh,
- ⇨ small space-charge accumulation and very fast signals

> “Optimum gap provides stable operation and minimizes gain variation from pressure-temperature variations and fluctuations due to gap variations”
>
> Y. Giomataris, CEA-Irfu-France



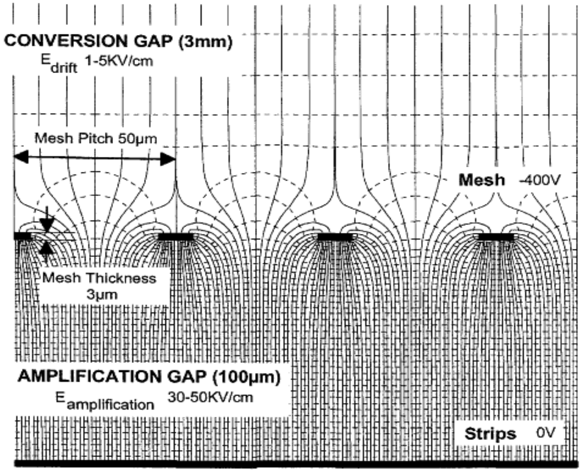
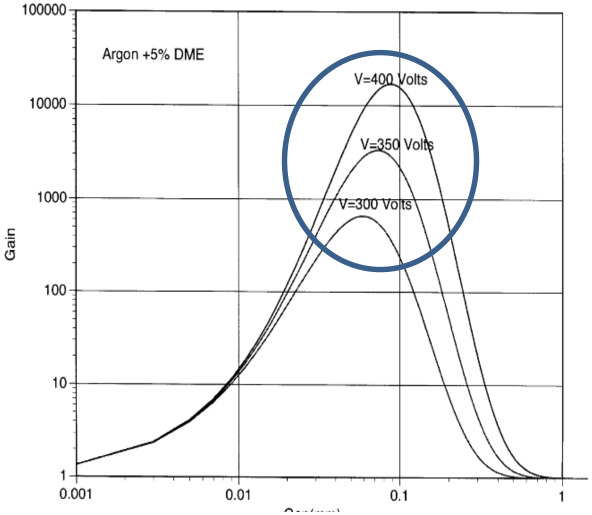


Fig. 1. Micromegas electric field map.

Y. Giomataris, Nucl. Instr. and Meth. A419 (1998)



$$M = e^{\alpha d}, \qquad \alpha = pAe^{-Bp/E}$$

maximum value is for $d = V/B$ at $p = 1$ bar.

$$M = e^{Apde^{-Bpd/V}}$$

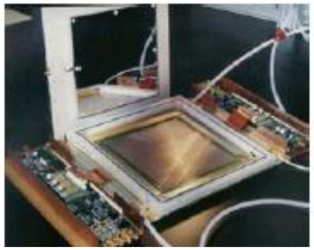
$$\frac{\delta M}{M} = \alpha d\left(1 - \frac{Bd}{V}\right)\frac{\delta d}{d}$$

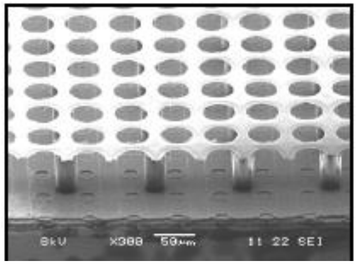
- ⇨ Gap around 100 μm: small gap variations compensated by an inverse variation of amplification factor
- ⇨ i.e. good uniformity and stability of response over a large area.

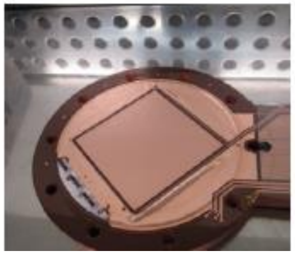
E. Ferrer Ribas, AERES – 8th January 2014

Micromegas

	CLASSICAL 1996	BULK 2003	INGRID 2005	MICROBULK 2006
Mesh Readout plane	TWO mechanical entities	INTEGRATED: ONE single entity		
Type of mesh	Any type	30 µm Stainless steel	1 µm Aluminium	5 µm Copper
Advantages	Demontability Large Surface	Robust Industrial manufacturing process (PCB)	Excellent energy resolution Single electron efficiency	Intrinsically Flexible Low mass Radiopure







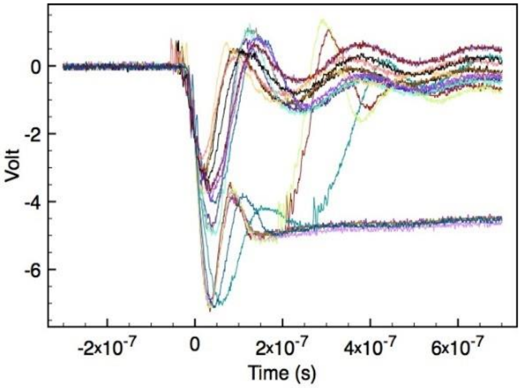
E. Ferrer Ribas, AERES – 8th January 2014

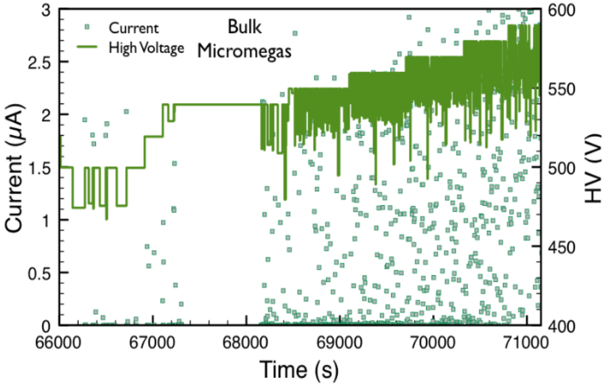
Micromegas: Resistive

No resistive Micromegas

Unacceptable rate of discharge with standard Micromegas

- ⇨ Not destructive for the detector ⇨ Robust and sturdy device
- ⇨ **However: long dead time and discharge critical for the FE chips (need to be very well protected)**





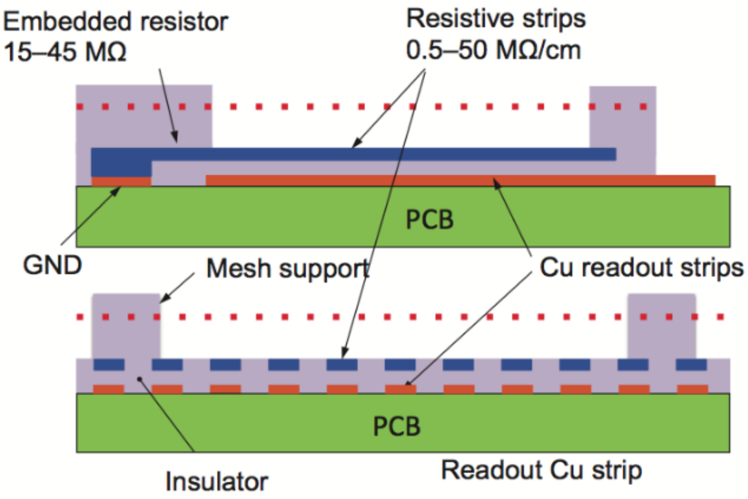
Spark signals on the oscilloscope (on 50 Ω, attenuated 1:100) and under neutron irradiation

J. Wotschack et al, Large-size Micromegas for ATLAS (MAMMA), RD51 mini week, 17/01/2011

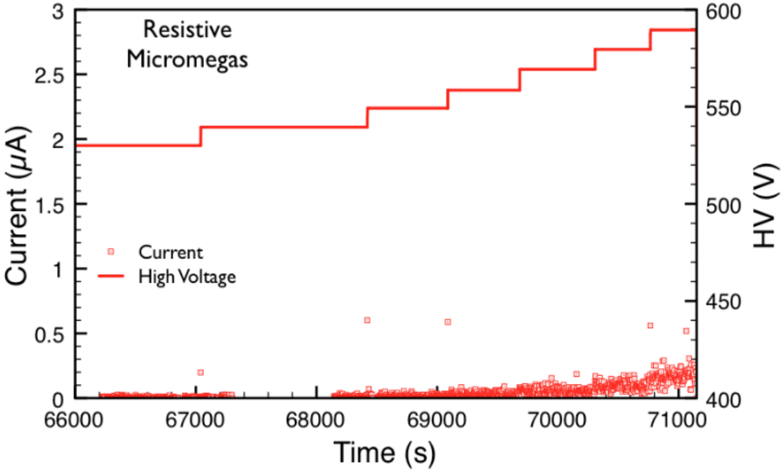
R&D effort by the RD51 Coll & the ATLAS Muon Upgrade

- ⇨ playing with the induction of the signal in the readout to protect against the damaging effects of spark
- ⇨ A sketch (not in scale) of the resistive-strip protection principle with a view along and orthogonal to the strip direction
- ⇨ Induced signal on the strips (no direct collection charges)

Resistive Micromegas



Monitored HV (continuous line) and current (point) as a function of HV mesh under neutron irradiation for a Micromegas

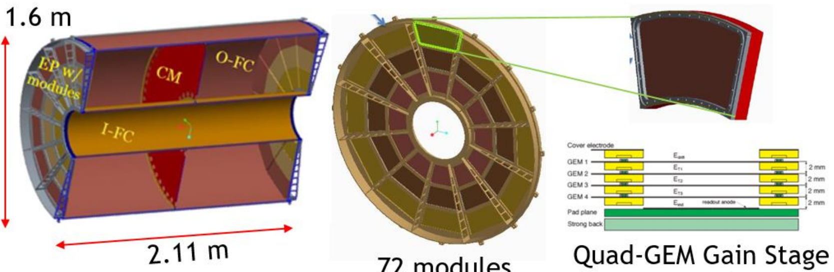


G. Iakovidis, arXiv:1310.0734v1 [physics.ins-det] 2 Oct 2013

MPGDs in all shapes and forms

Disk: Forward Tracker or TPC endcap

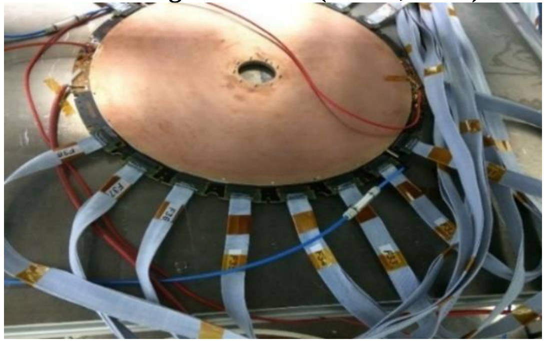
TPC GEM readout, sPHENIX @ BNL



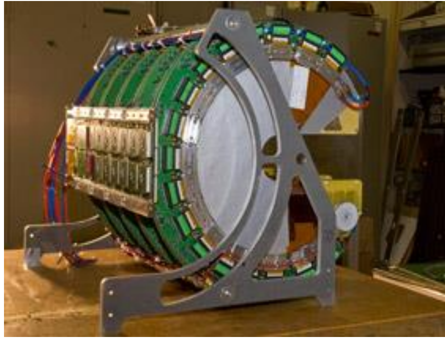
72 modules
2(z), 12(ϕ), 3(r)

Quad-GEM Gain Stage
Operated @ low IBF

Micromegas CLAS12 (Hall B, JLab)

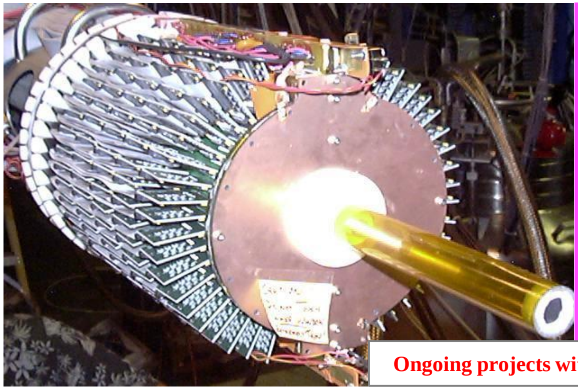


TOTEM GEM @ LHC CERN



Cylindrical: Central tracker or Radial TPC

GEM: BoNuS rTPC in Hall B @ JLab

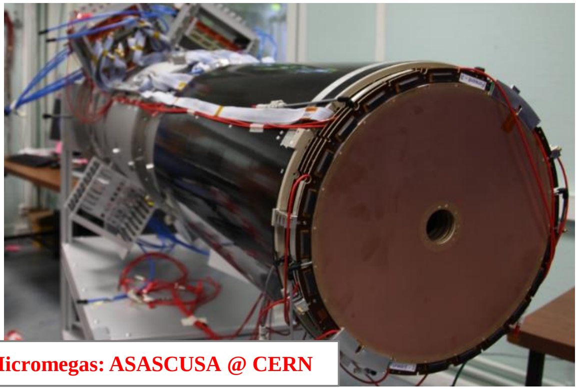


E. Christy
Tagged SF, JLAB 2014

GEM KLOE-2 @ Frascati,

D. Domenici
INSTR2014, Novosibirsk

Micromegas CLAS12 (Hall B, JLab)

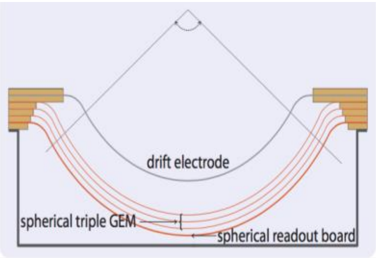


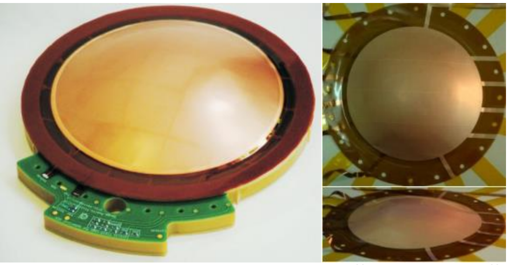
M. Vandenbroucke, MPGD2015
Trieste, Italy

Ongoing projects with cylindrical MPGDs: GEMs: TDIS, BoNus12 in JLab, BES III (China), Micromegas: ASASCUSA @ CERN

Spherical GEM

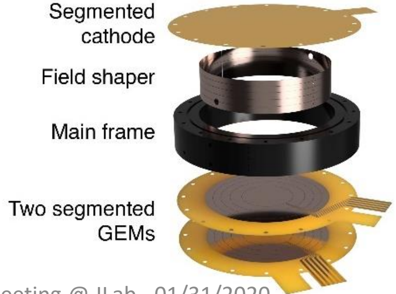
S. Pinto, https://arxiv.org/pdf/1011.5528.pdf

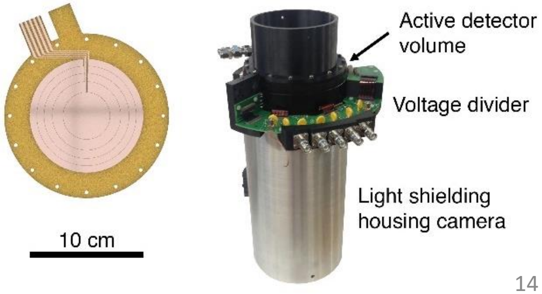




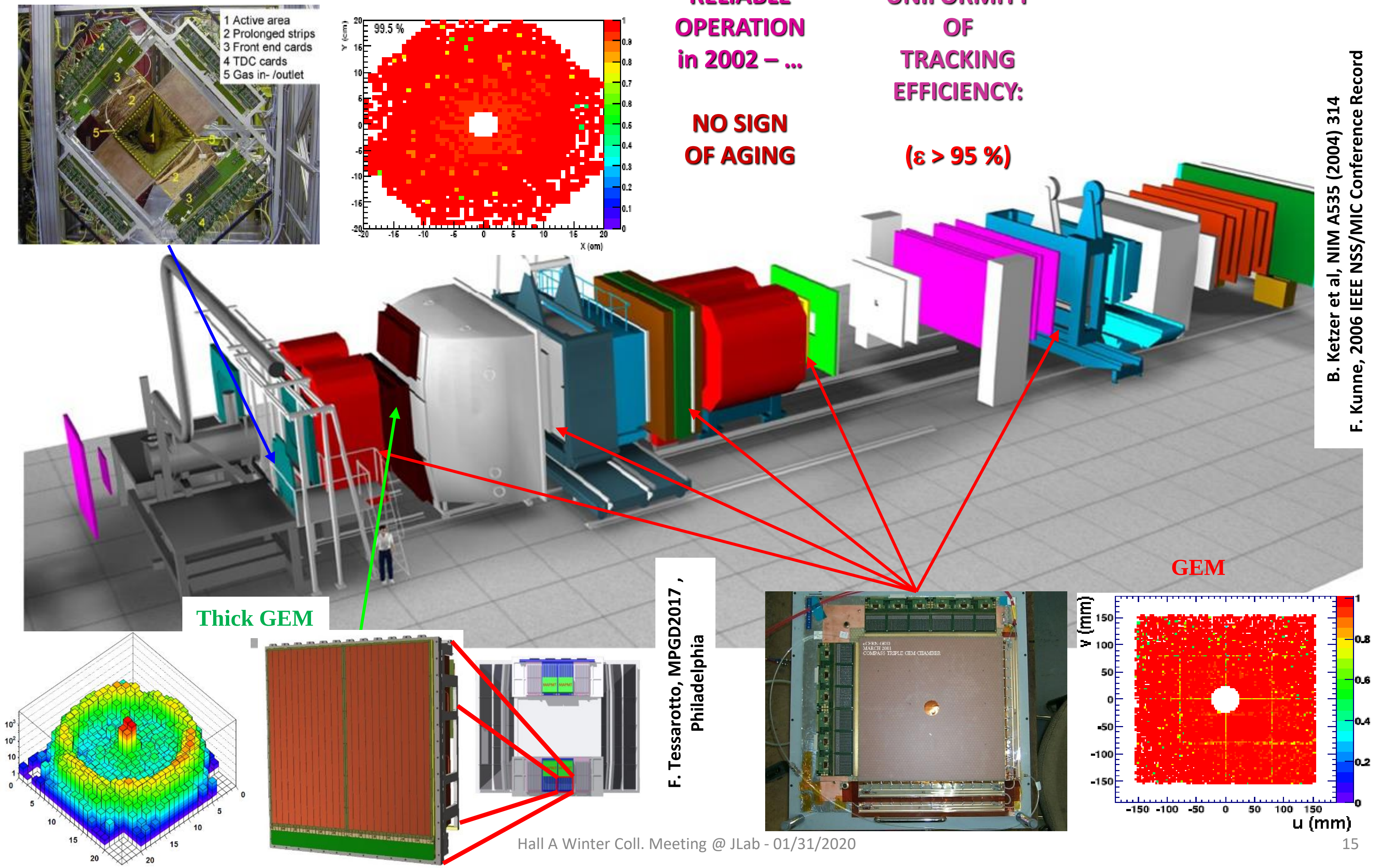
Planispherical GEM

F. Sauli, RD51 Coll. Meeting, Aveiro 2016





COMPASS: Standard Bearer for MPGDs in HEP Experiments



MICROMEGAS

RELIABLE OPERATION in 2002 – …

NO SIGN OF AGING

UNIFORMITY OF TRACKING EFFICIENCY:

(ε > 95 %)

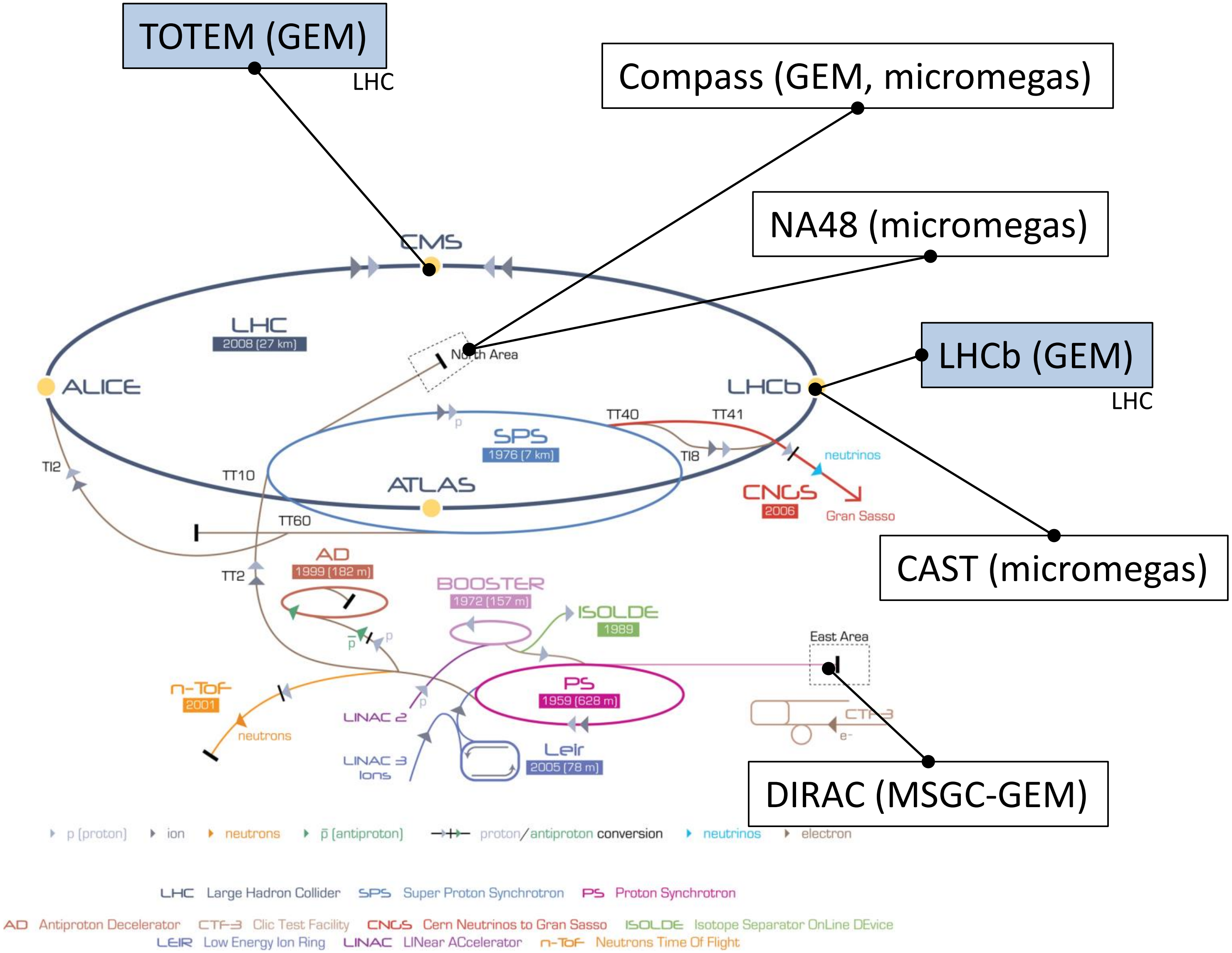
Thick GEM

GEM

B. Ketzer et al, NIM A535 (2004) 314
F. Kunne, 2006 IEEE NSS/MIC Conference Record

F. Tessarotto, MPGD2017 , Philadelphia

MPGDs @ CERN: Running Experiments


TOTEM (GEM)
LHC

Compass (GEM, micromegas)

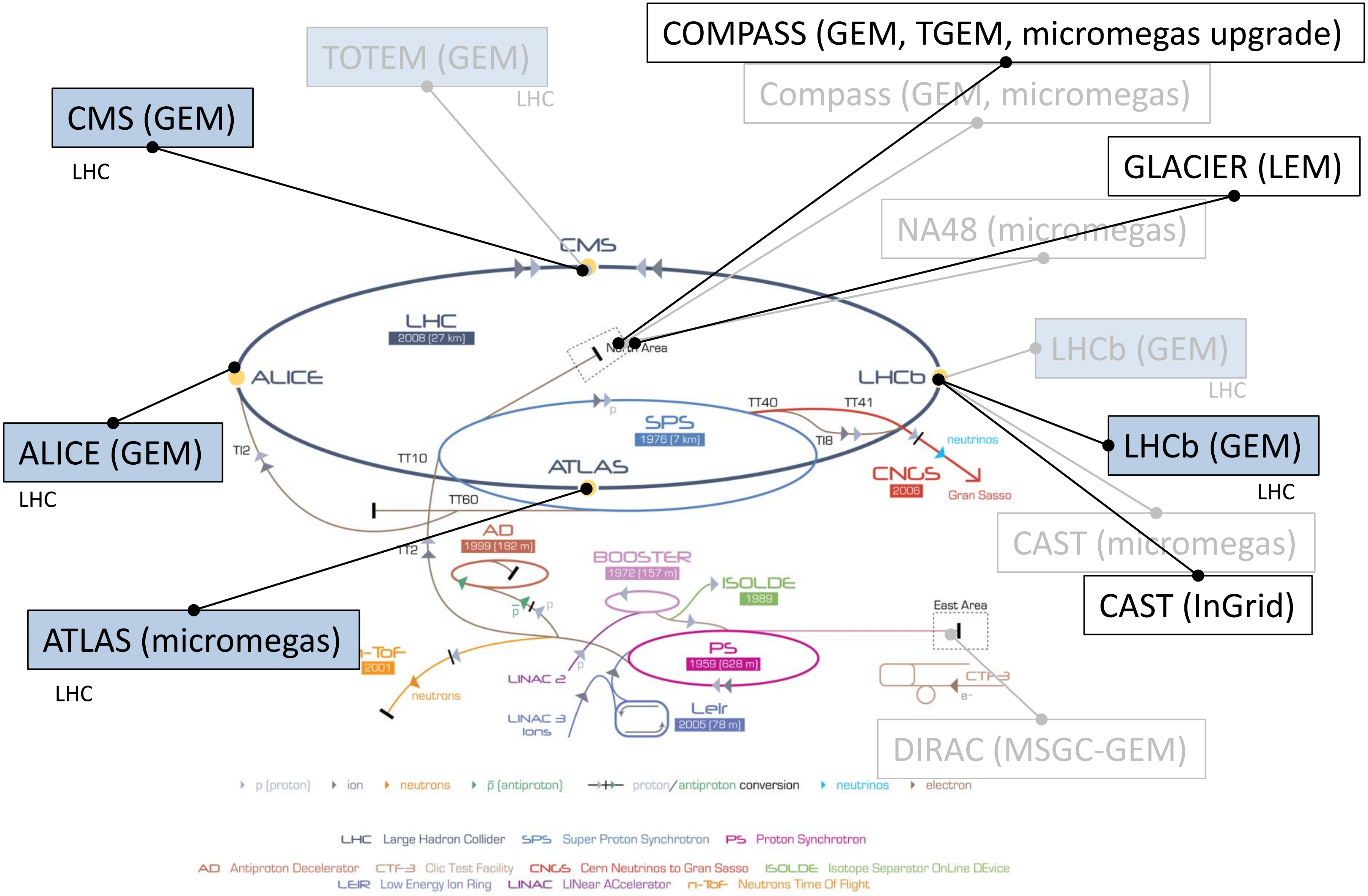
NA48 (micromegas)

LHCb (GEM)
LHC

CAST (micromegas)

DIRAC (MSGC-GEM)

MPGDs @ CERN: Running Experiments



TOTEM (GEM)
LHC

CMS (GEM)
LHC

COMPASS (GEM, TGEM, micromegas upgrade)

Compass (GEM, micromegas)

GLACIER (LEM)

NA48 (micromegas)

LHCb (GEM)
LHC

ALICE (GEM)
LHC

LHCb (GEM)
LHC

CAST (micromegas)

CAST (InGrid)

ATLAS (micromegas)
LHC

DIRAC (MSGC-GEM)

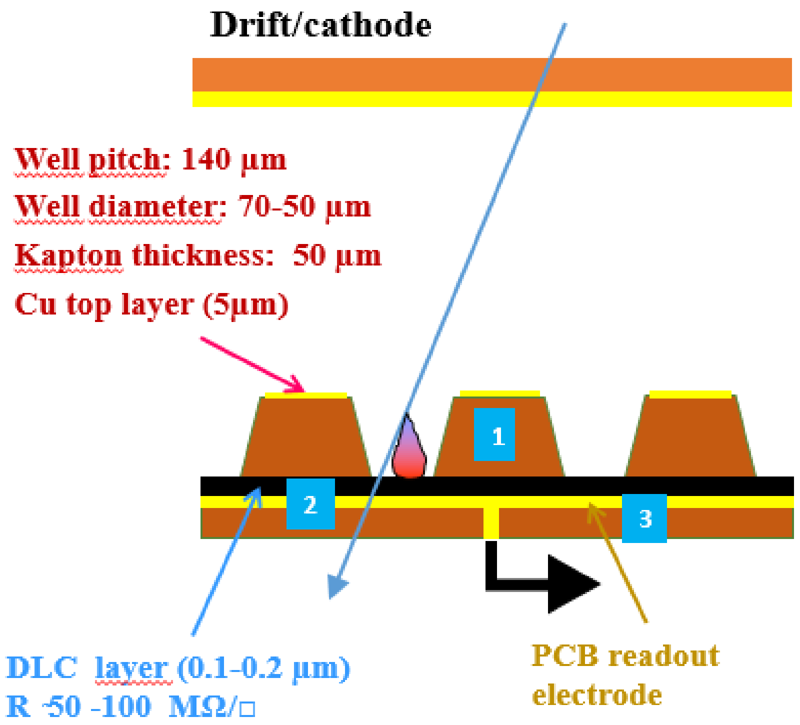
New MPGD Structures: Micro Resistive Well detector

The μ-RWELL detector is composed of two parts: the **cathode** and the **μ-RWELL_PCB .**

The **μ-RWELL_PCB** is realized by **coupling:**

1. **a** “**suitable WELL patterned kapton foil** as “amplification stage”
2. **a “resistive stage”** for the discharge suppression & current evacuation:
   i. **“Low particle rate” (LR)** << 100 kHz/cm^2**:** single resistive layer → surface resistivity ~100 MΩ/□ (CMS-phase2 upgrade - SHIP)
   ii. **“High particle rate” (HR)** >> 100 kHz/cm^2: more sophisticated resistive scheme must be implemented (MPDG_NEXT- LNF & LHCb-muon upgrade)
3. **a standard readout PCB**

μ-RWELL PCB



G. Bencivenni et al., 2015_JINST_10_P02008

G. Bencivenni, RD51 Coll. meeting, Aveiro, 09/2016

New MPGD Structures: Micro Resistive Well detector

Best of both worlds

⇨ Like Micromegas ⇨ One amplification stage, no need to stretched etc …

⇨ Like GEM ⇨ Simple structure (Just like GEM foil); ideal for a full cylindrical detector

⇨ possibility to add a pre-amplification GEM foil if needed

⇨ **Gain: is one order of magnitude higher gain than a single GEM at the same bias voltage**

⇨ **Spark rate: Very low spark rate and current**

⇨ **Robust and simple detector**

Current limitation of this technology is its rate capability compared to GEM detectors

⇨ **similar issue as for Resistive Micromegas**

⇨ Study of electrical properties of resistive materials that allow high rate and quenched discharge

⇨ The goal is to reach a rate > 1 MHz / cm2

G. Bencivenni et al, doi:10.1088/1748-0221/10/02/P02008

Single GEM

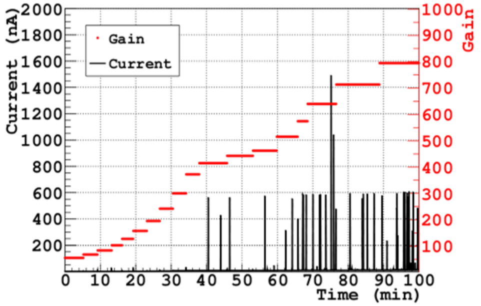


Figure 9. Monitoring of the current drawn (in black) by the single-GEM detector for different gas gain (in red). Discharge amplitudes as high as 1μA are recorded at higher gains.

μ-RWell

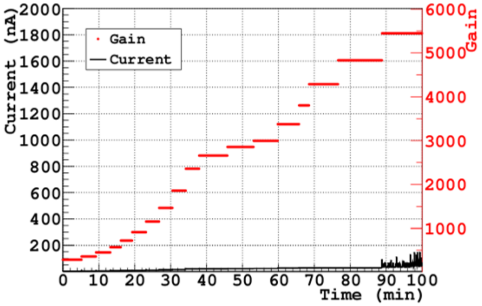


Figure 10. Monitoring of the current drawn (in black) by the μ-RWELL detector for different gas gain (in red). Discharges are quenched down to few tens of nA even at high gains.

Performance at high rate

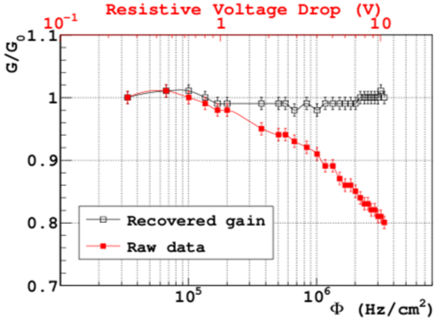


Figure 11. Normalized gain (a.u.) for the μ-RWELL as a function of the flux: full squares are the raw data; open squares are obtained increasing the voltage (of a value reported on the upper horizontal axis) in order to recover the gain ($G_0 = 2000$ with Ar:CO$_2$ 70:30).

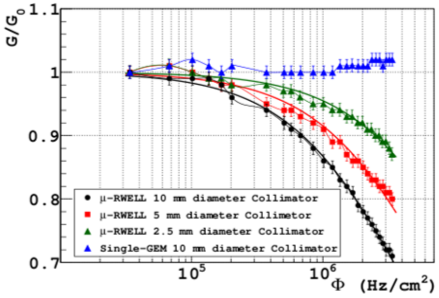
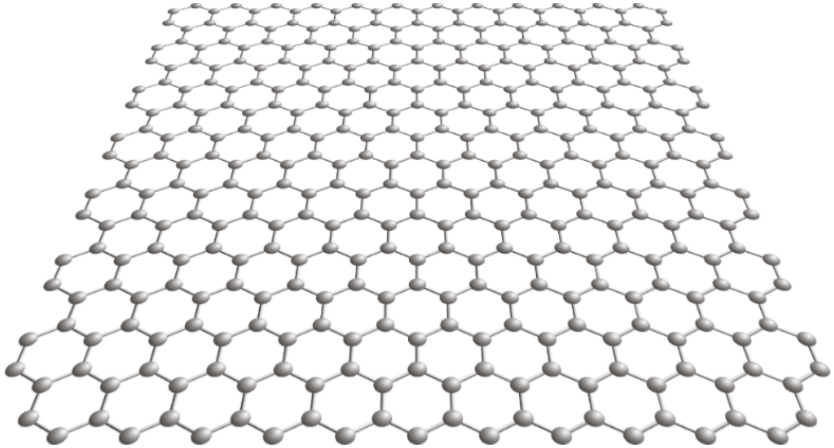


Figure 12. Comparison of the normalized gain (a.u.) for the GEM (blue) and the μ-RWELL for different collimator diameters (10 mm — black; 5 mm — red; 2.5 mm — green) pointing at the center of the active area ($G_0 = 2000$ with Ar:CO$_2$ 70:30).

New Structures: Graphene MPGDs

Graphene



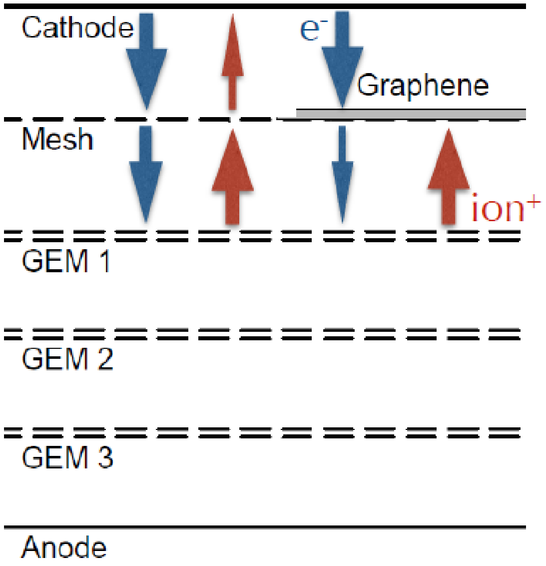
A **single layer of carbon atoms** arranged in a hexagonal lattice, Regarded as thinnest possible **conductive mesh** with **pore size ~ 0.6 Å**

Why it is interesting

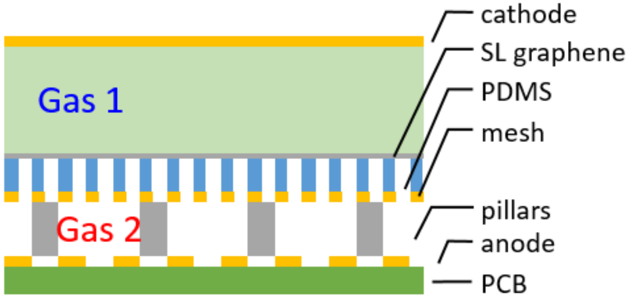
- **Strong asymmetry** in electron and ion transmission through graphene
- **Mechanically robust** accounting for its thickness: can be freely suspended over (tens of) micrometres
- A **membrane fully transparent to electrons** and **fully opaque to ions**
  - **Eliminating ion back-flow in gaseous detectors**
  - **Protecting photo-cathodes**
  - **Enabling the use of different gases in same detector**

Potential applications

ion back-flow in gaseous detectors



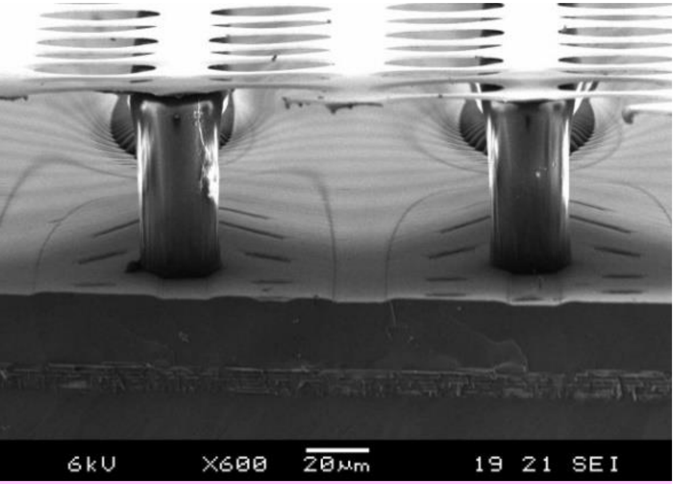
different gases in same detector



P. Thuyner, RD51 Coll. meeting, Aveiro, 09/2016

New Structures: GridPix (InGrid + Timepix)

Combine:
Gaseous amplification (Micromegas)
&
Silicon readout (Timepix)



Christoph Krieger RD51 Week, CERN,06/19/2014

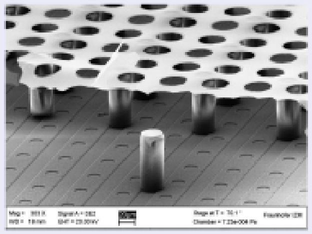
Integrated Micromegas – InGrid

Chefdeville et al - Nucl. Inst. Meth. A 556(2006), p 490

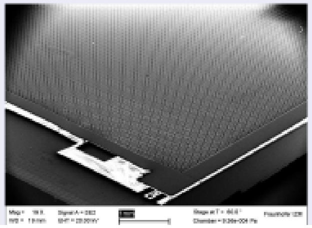
Micromegas on top of Timepix ASIC

- Fabrication by means of photolithographic postprocessing
- Very good alignment of grid and pixels
- Each avalanche is collected on one pixel
- Detection of single electrons possible

InGrid - SEM



Timepix + InGrid



Production of InGrids

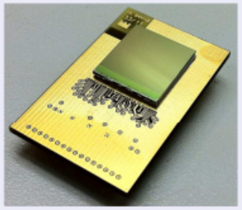
- Single and few chip processing: NIKHEF / Mesa+ (Twente)
- Wafer processing ($\sim$ 100 chips at once): in cooperation with IZM Berlin

Timepix

Facts about the Timepix ASIC

- 256×256 pixels, $55 \times 55\,\mu m^2$ pitch
- $1.4 \times 1.4\,cm^2$ active area
- Charge sensitive amplifier and discriminator in each pixel, $90\,e$ ENC
- Two modes: **Charge** or **Time**

Carrier board

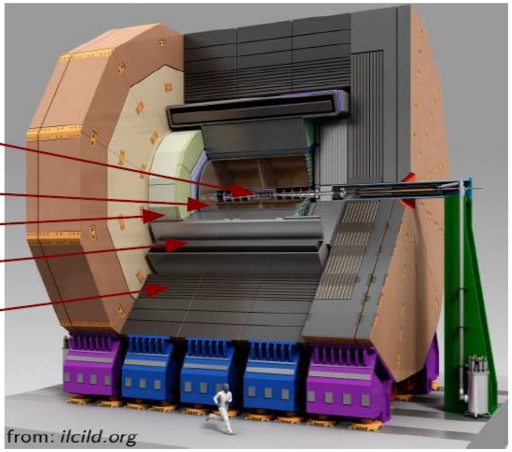


Energy Resolution

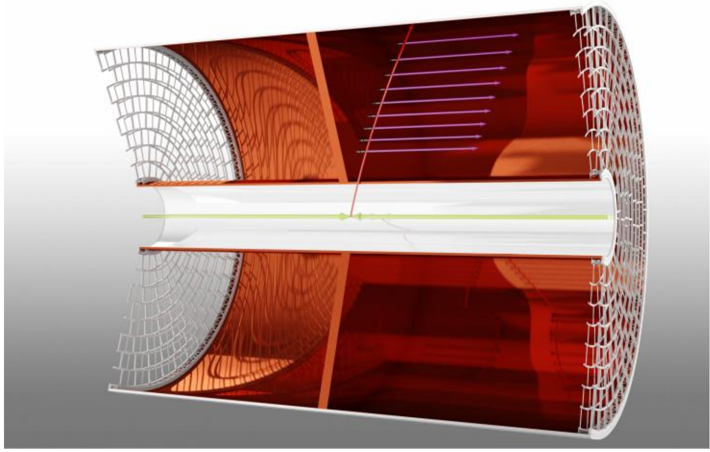
- Resolutions down to $\sigma_E/E \approx 3.85\,\%$ at 5.9 keV were observed in Ar/iC$_4$H$_{10}$ 90/10 at optimized settings (Energy determined from pixel counting)
- In Ar/iC$_4$H$_{10}$ 97.7/2.3 resolutions down to $\sigma_E/E \approx 5.33\,\%$ at 5.9 keV are possible

New Structures: GridPix (InGrid + Timepix)

- ILD: A general purpose 4π detector
  - Vertex detector
  - Tracking detector:
    Time Projection Chamber (TPC)
  - Calorimeter
  - Magnet system
  - Muon detector



from: *ilcild.org*



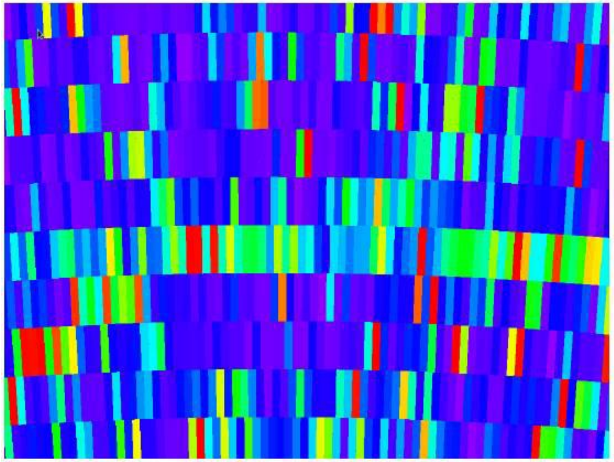
High resolution TPC readout

approach: match readout segmentation to MPGD cell size

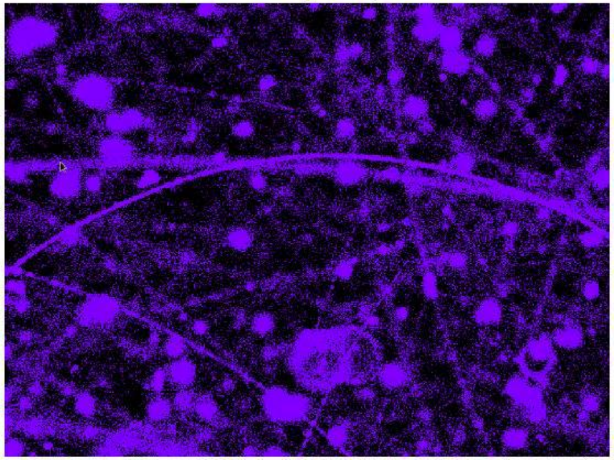
Use ASIC with charge sensitive pixels

- Charge treated in analogue section
- Digital output
- High density electronics
- Include gas amplification stage

1×6 mm^2 pads



100×100 μm^2 pixels

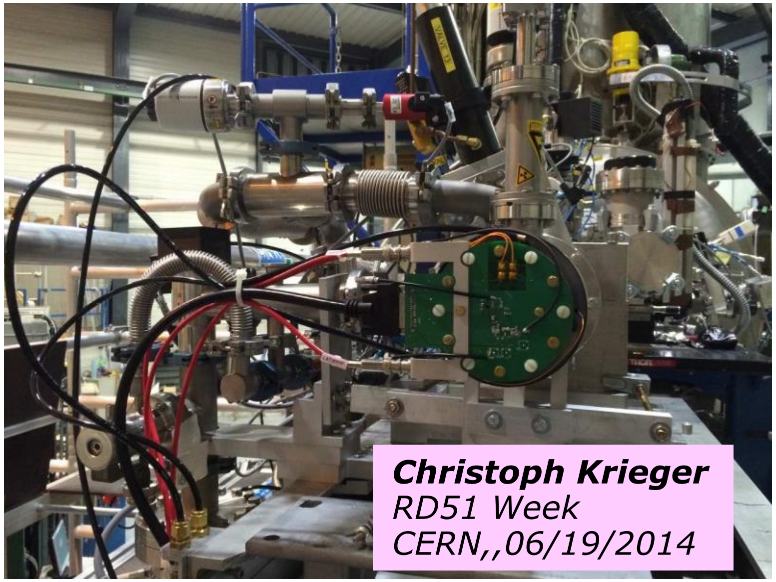


***M. Lupberger,** RD51 Coll. Meeting, Aveiro, 09/2016*

New Structures: GridPix (InGrid + Timepix)

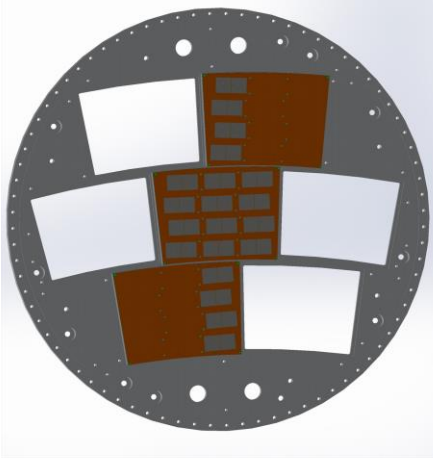
CAST Experiment
CERN Axion Solar Telescope

InGrid detector @ CAST

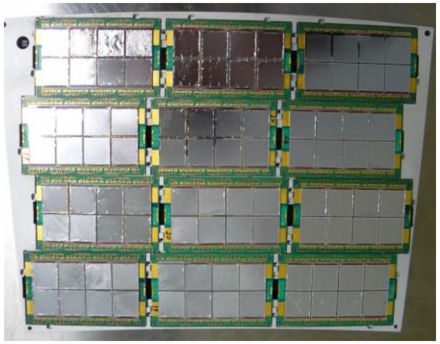


Christoph Krieger
RD51 Week
CERN,,06/19/2014

R&D ILC TPC readout

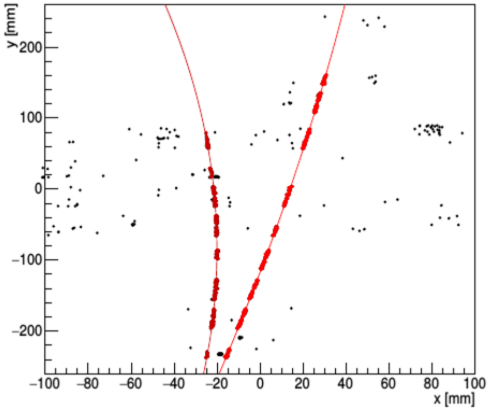


Module production

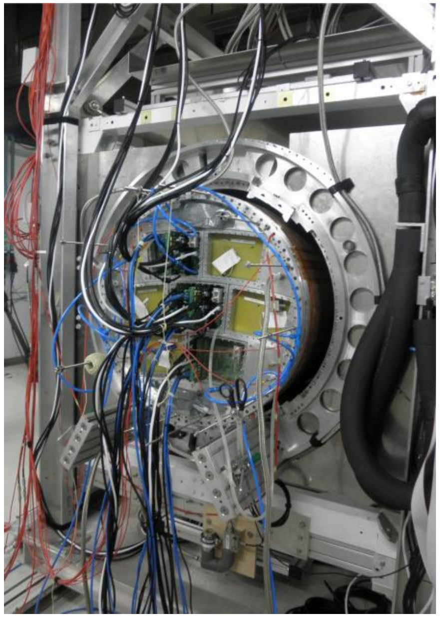


***J. Kamiski,** MPGD2015*
Trieste, Italy, 10/12/2015

Track reconstruction



Test beam



GEM Trackers for SBS, MOLLER, SoLID …

MPGDs in Hall A @ JLab: SBS GEM Trackers

Nucleon form factors

Electromagnetic current density of nucleon:

$$\mathcal{J} = e\bar{N}(p')\left[\gamma^\mu F_1(Q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2M}F_2(Q^2)\right]N(p)$$

- Encode electric and magnetic structure of the nucleon
- Parametrize the properties of the quark and gluon
- Limited neutron measurements in terms the Q^2 range and the precision
- Better access to relatively small G_E
- No recoil polarimetery measurement above Q^2 of 1.5 GeV^2

$$G_E = F_1 - \tau F_2$$
$$G_M = F_1 + F_2$$

In High Q^2 range:

→ G_E measurement will sensitive to up and down quark distributions in quark core

→ Insight to the complete set of form factors in the region with small pion cloud contributions

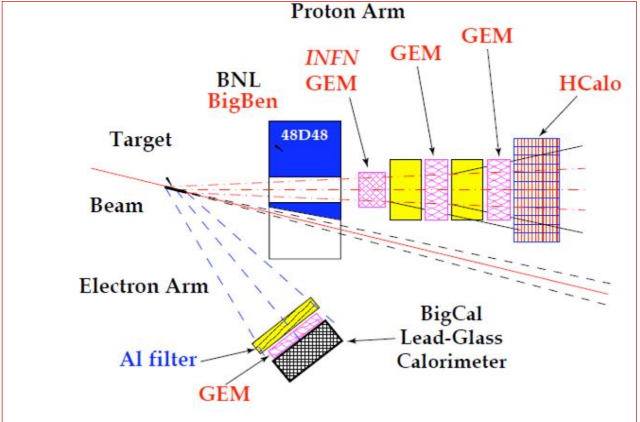
The Super-BigBite Spectrometer (SBS) in Jlab's Hall A will measure the G_E to high Q^2 (>10 GeV^2) using high luminosity + open geometry + GEM detectors

→ Allows for flavor decomposition to distance scales deep inside the nucleon

SBS GEM trackers:

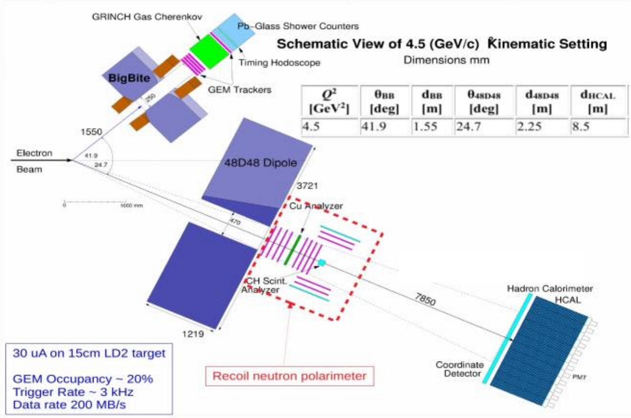
- High counting rate (~ **400 kHz/cm^2**) expected at highest luminosity of **10^{39}** electrons/s-nucleon/cm^2
- Large acceptance & small field integral magnet ⇨ Excellent Spatial resolution (**70 µm**)
- Low cost for large tracking system when compared to silicon trackers and high rate compared to Drift chambers

GEp (5): Proton Form Factor @ high Q^2



E12-07-109: measurement of G^p_E/G^p_M up to Q^2=12 GeV^2 using a target of liquid hydrogen

GEn-RP: Neutron Form Factor



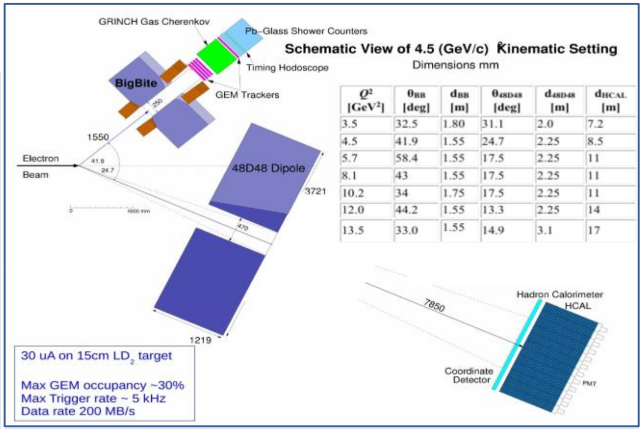
Q^2 [GeV^2]	θ_{BB} [deg]	d_{BB} [m]	θ_{48D48} [deg]	d_{48D48} [m]	d_{HCAL} [m]
4.5	41.9	1.55	24.7	2.25	8.5

30 uA on 15cm LD2 target

GEM Occupancy ~ 20%
Trigger Rate ~ 3 kHz
Data rate 200 MB/s

E12-17-004: measurement of G^n_E/G^n_M up to Q^2=4.5 GeV^2 polarized deuterium target

GEn & GMn: Neutron Form Factor @ high Q^2



Q^2 [GeV^2]	θ_{BB} [deg]	d_{BB} [m]	θ_{48D48} [deg]	d_{48D48} [m]	d_{HCAL} [m]
3.5	32.5	1.80	31.1	2.0	7.2
4.5	41.9	1.55	24.7	2.25	8.5
5.7	58.4	1.55	17.5	2.25	11
8.1	43	1.55	17.5	2.25	11
10.2	34	1.75	17.5	2.25	11
12.0	44.2	1.55	13.3	2.25	14
13.5	33.0	1.55	14.9	3.1	17

30 uA on 15cm LD$_2$ target

Max GEM occupancy ~30%
Max Trigger rate ~ 5 kHz
Data rate 200 MB/s

E12-09-019: measurement of G^n_M/G^p_M up to Q^2=13.5 GeV^2 polarized deuterium target.
E12-09-016: measurement of G^n_E/G^n_M up to Q^2=10 GeV^2 using a polarized ^{3}He target.

MPGDs in Hall A @ JLab: SBS GEM Trackers

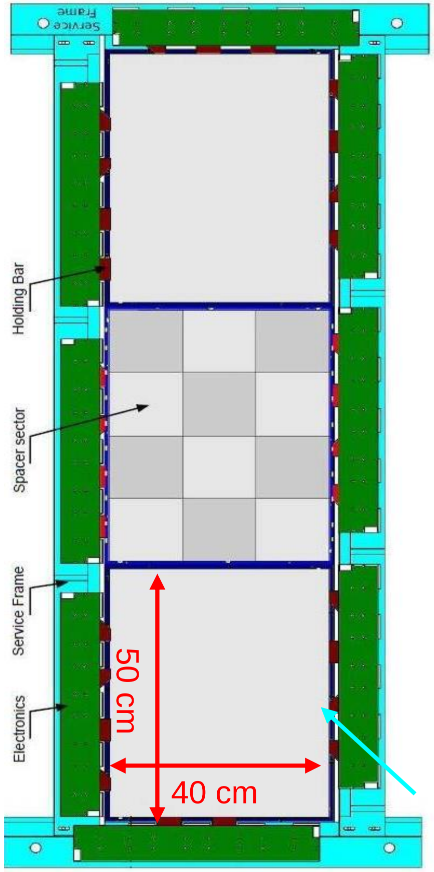
INFN GEMs: Front Trackers GEMs

- Design, Construction and Tests (INFN Catania & Roma)
- 6 GEM Layers active area (150 cm × 40 cm)
- Vertical stack of 3 GEM modules (50 cm × 40 cm)
- Production of 18 modules (+ spares)
- Currently at Jlab for commissioning

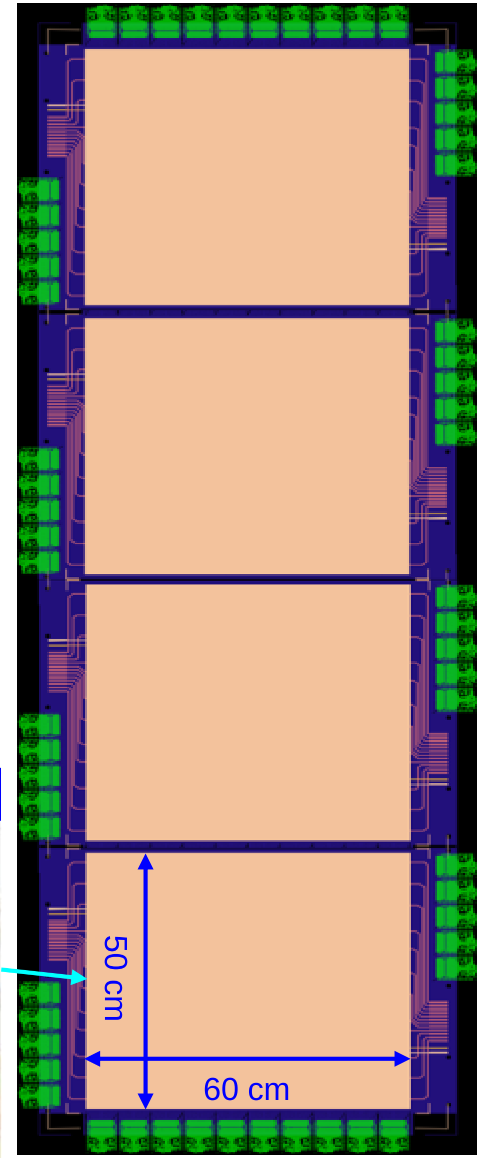
UVa GEMs: Back Trackers GEMs – Proton Recoil Polarimeters

- Design, Construction and Tests @ University of Virginia (UVa)
- Total of 11 × GEM Layers active area (200 cm × 60 cm)
- Vertical stack of 4 × GEM modules (60 cm × 50 cm)
- Production of 44 modules (+ spares)
- Currently at JLab for commissioning

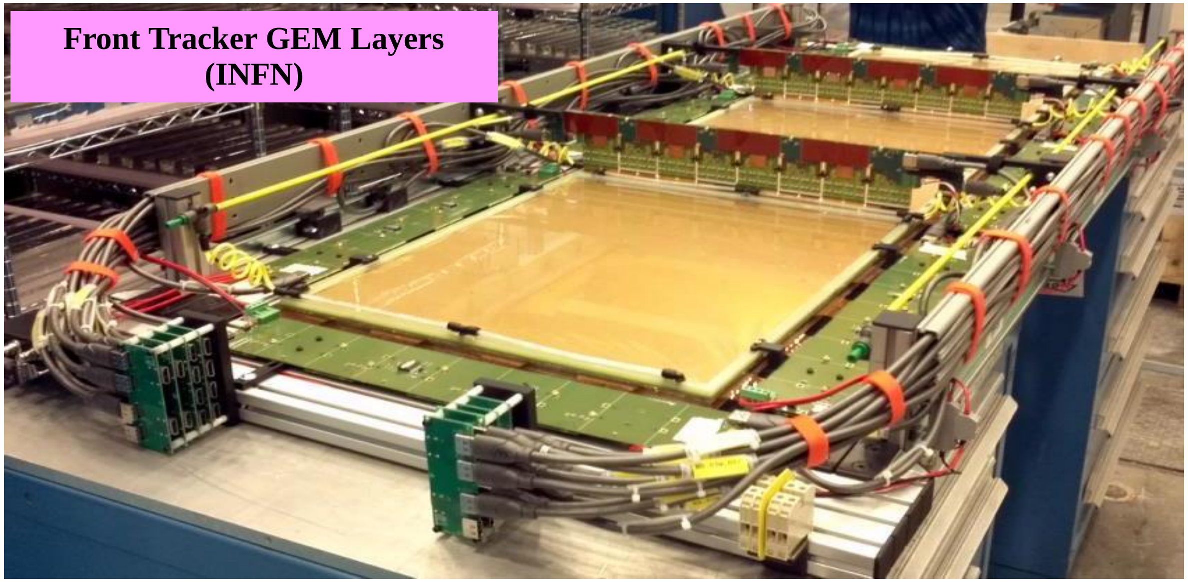
INFN GEM layer



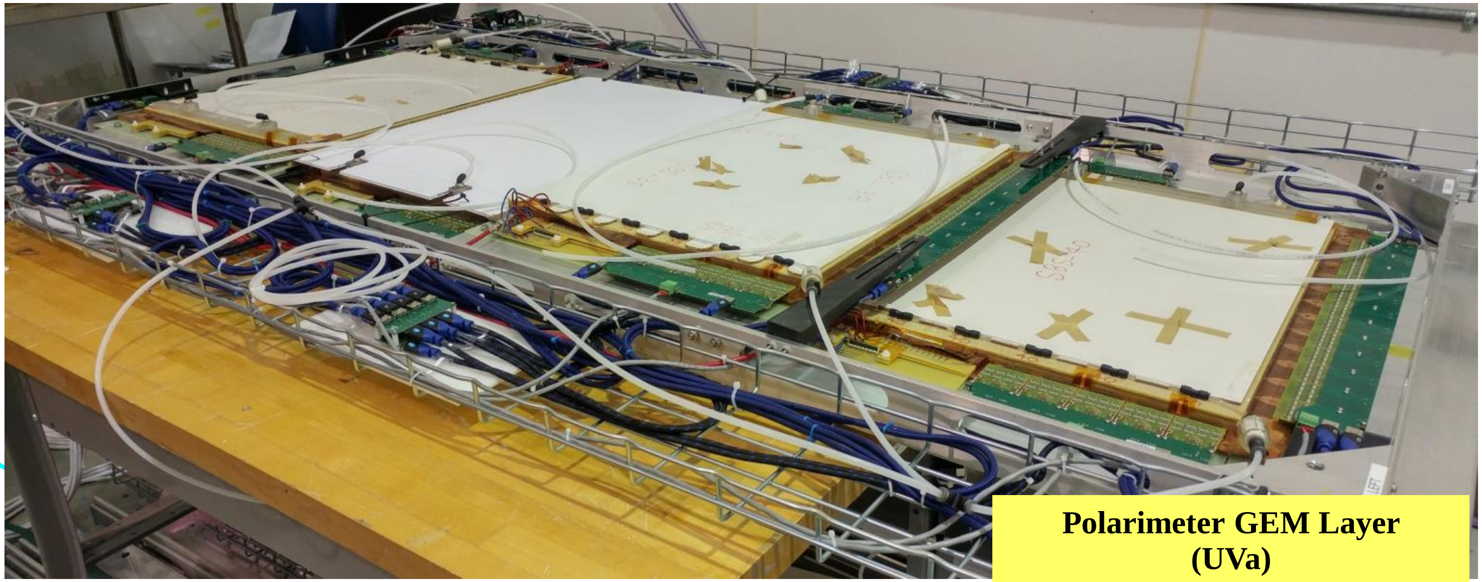
UVa GEM layer



MPGDs in Hall A @ JLab: SBS GEM Trackers

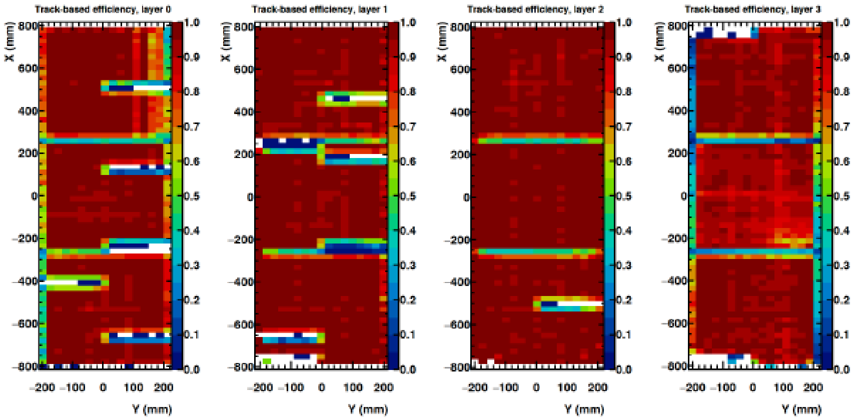


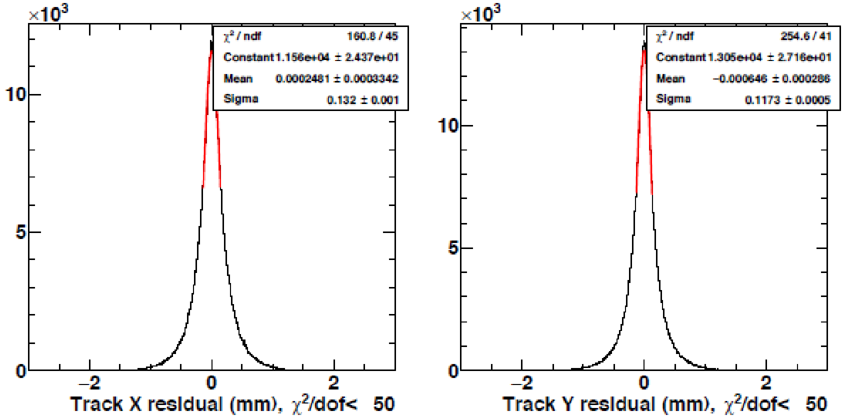
Front Tracker GEM Layers
(INFN)



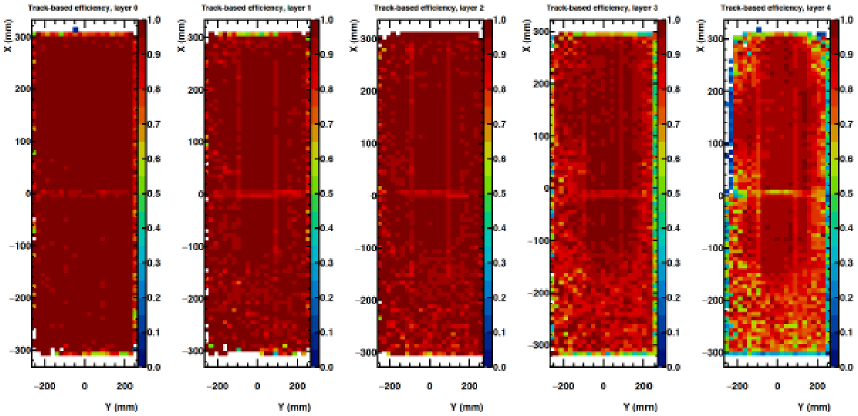
Polarimeter GEM Layer
(UVa)

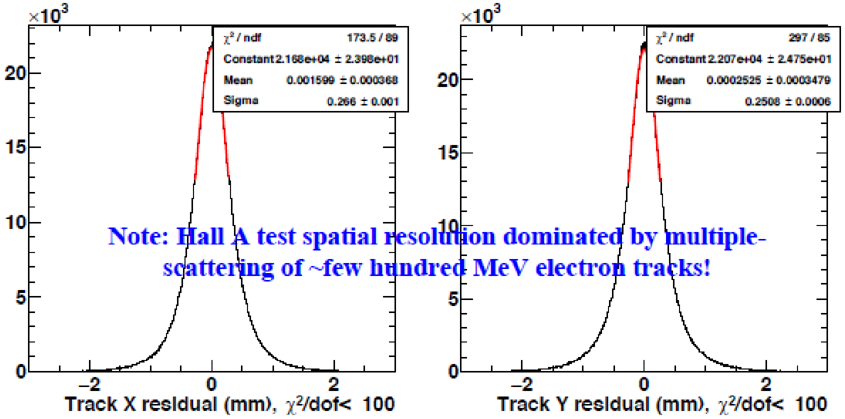
Tracking residuals and track based efficiency





- Above, left: “track based” local GEM efficiency from INFN 4-layer cosmic data, 2018
- Above, right: Tracking residuals from INFN cosmic data: $(\sigma_x, \sigma_y) = (132\ \mu m, 117\ \mu m)$



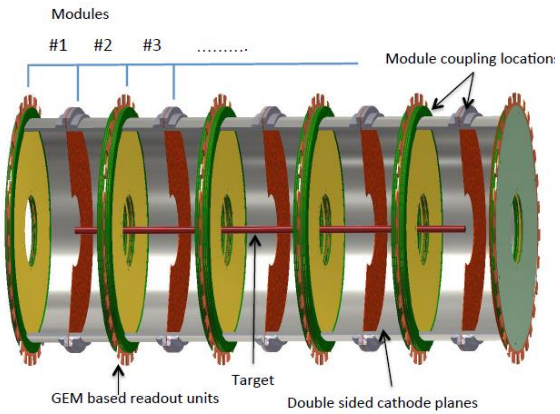


Note: Hall A test spatial resolution dominated by multiple-scattering of ~few hundred MeV electron tracks!

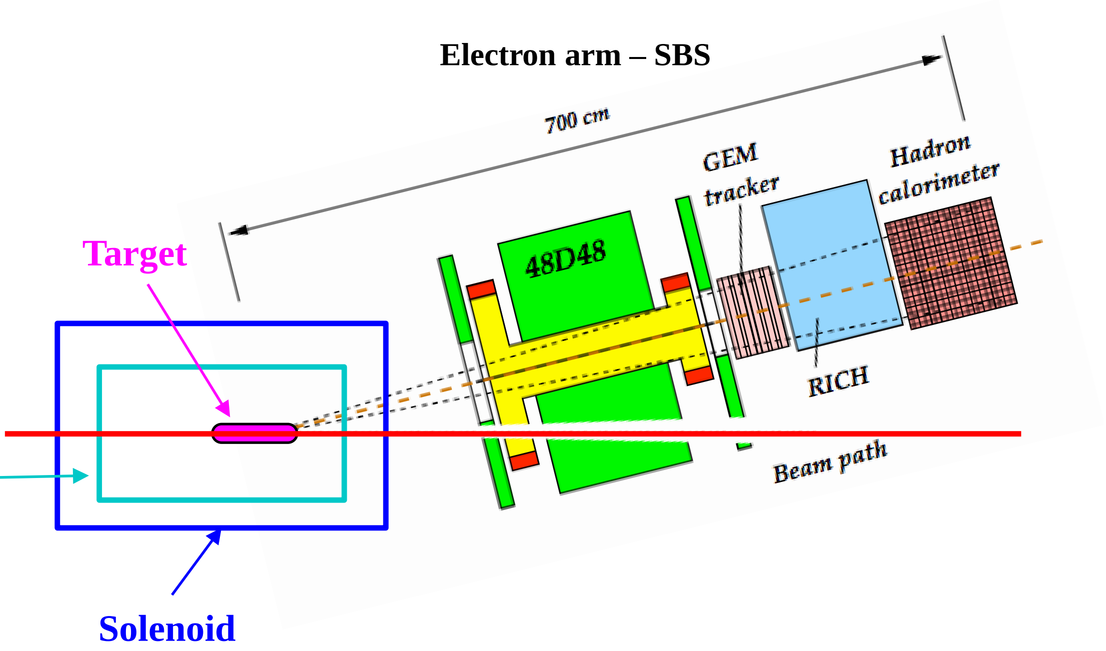
- Above, left: “track based” local GEM efficiency from UVA 5-layer Hall A data, 2016
- Above, right: Tracking residuals from UVA Hall A data: $(\sigma_x, \sigma_y) = (266\ \mu m, 251\ \mu m)$

MPGDs in Hall A @ JLab: TDIS mTPC

- **Electron arm:** Measure DIS cross section, detecting high W^2, Q^2 of scattered e- from H2 and D2 targets
- **Proton arm:** Coincidence tagging of low momentum recoil and spectator protons



mTPC



Electron arm – SBS

Target

Solenoid

Proton Arm

- **H2 or D2 Target:** Straw target (12 um Kapton cylinder with 10um Al end cap)
- **Proton Detector (mTPC) :** modular TPC consisting of stack of 10 sub modules
- **Solenoid:** 40 cm bore 5T super conductive solenoid magnet (UVa)

Electron Arm: SBS spectrometer

- **Tracker:** 5 SBS GEM planes
- **EM Calorimeter** (LAC from CLAS)
- **RICH** or threshold gas Cherenkov
- PID for trigger level 2: LAC + Cherenkov
- hadron calorimeter (HCAL) for quasi-elastic neutron calibration

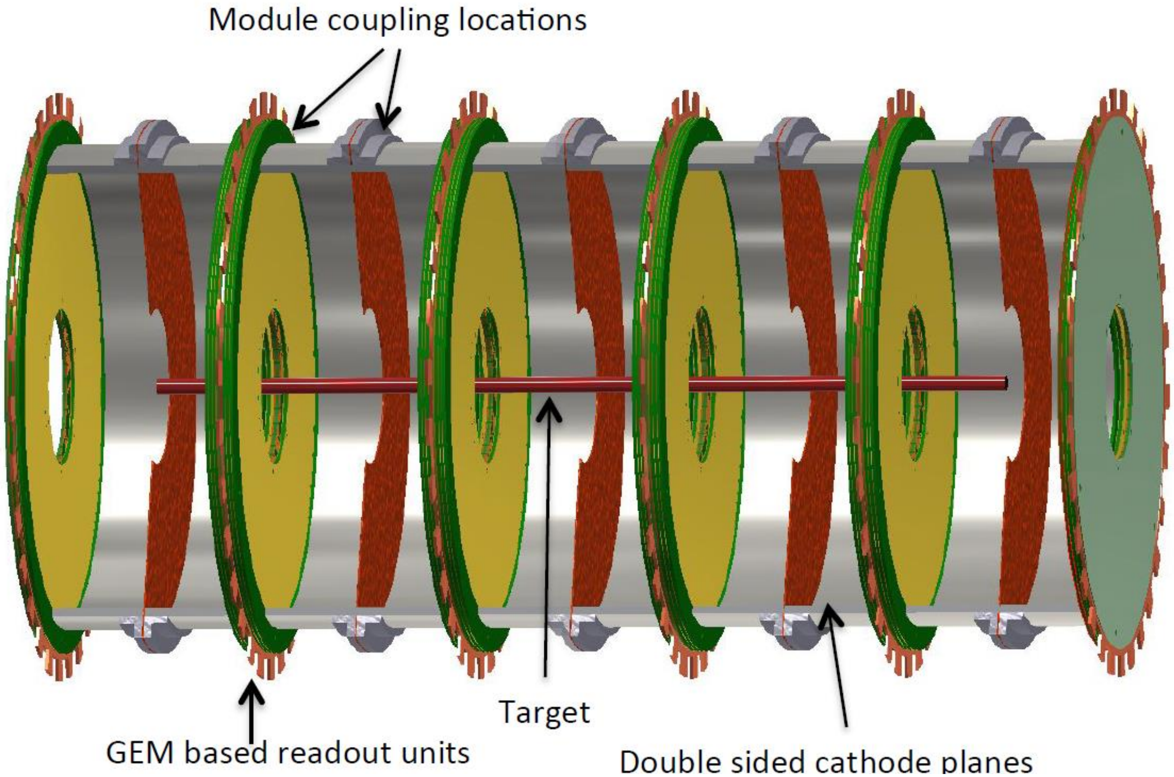
MPGDs in Hall A @ JLab: TDIS mTPC

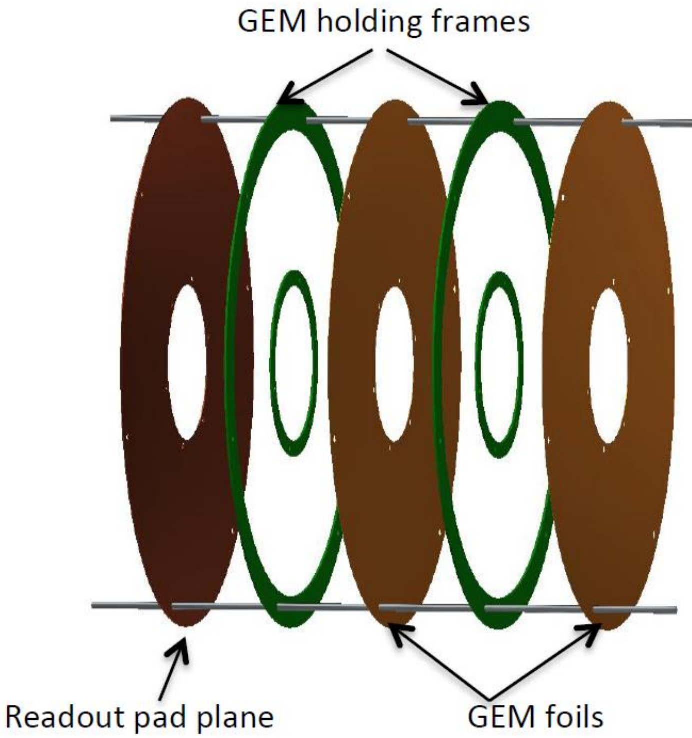
mTPC:

- Stack of 10 individual sub modules. Each sub module is a standalone TPC
- Gas mixture: He CH4 (90/10) at room temperature and atmospheric pressure

Sub module

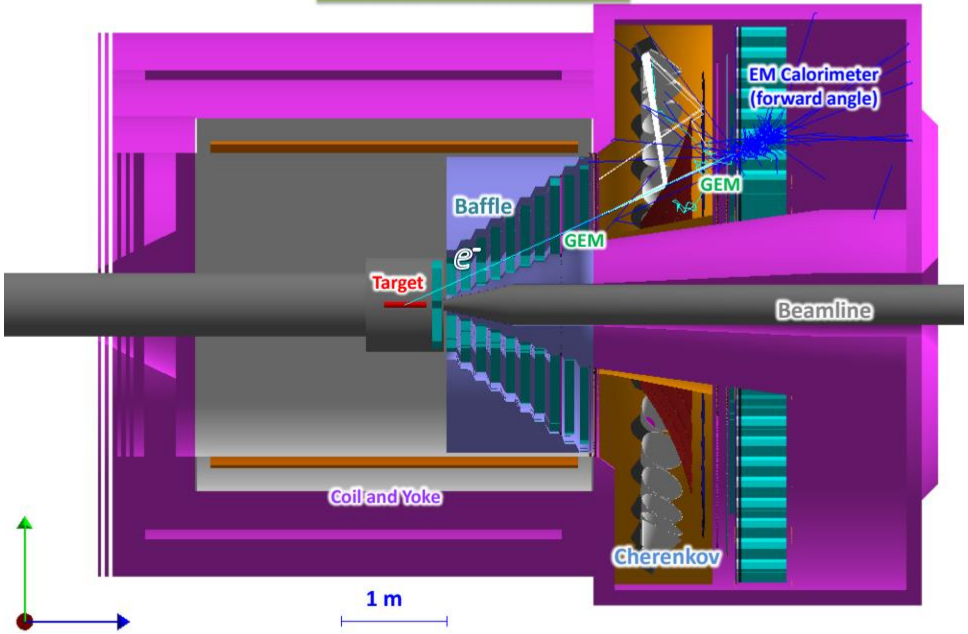
- 5cm drift volume, a 2 stack of GEM foils for the amplification and pad readout for the signal collection
- Drift Cathode foil is shared by two sub modules

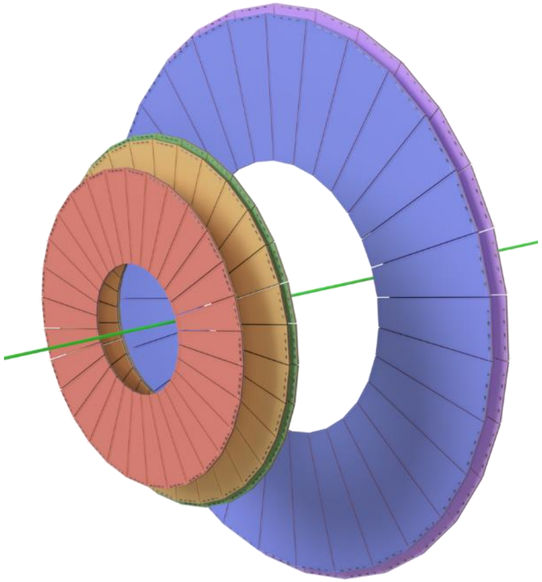


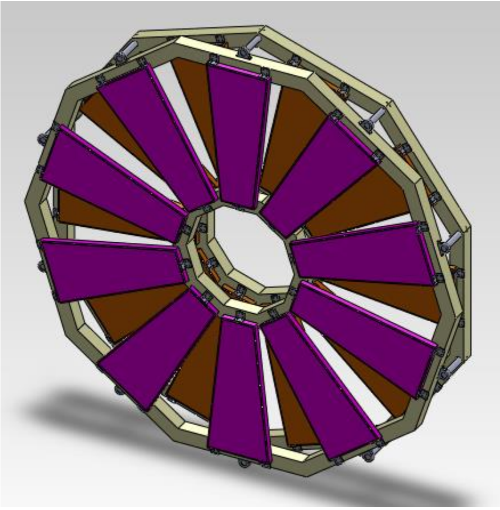


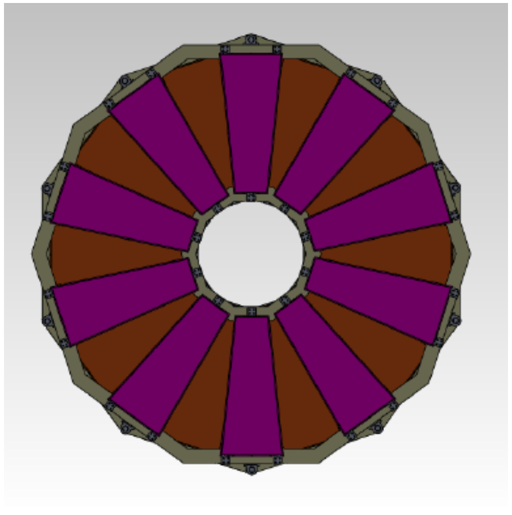
MPGDs in Hall A @ JLab: SoLID GEM

SoLID (PVDIS)

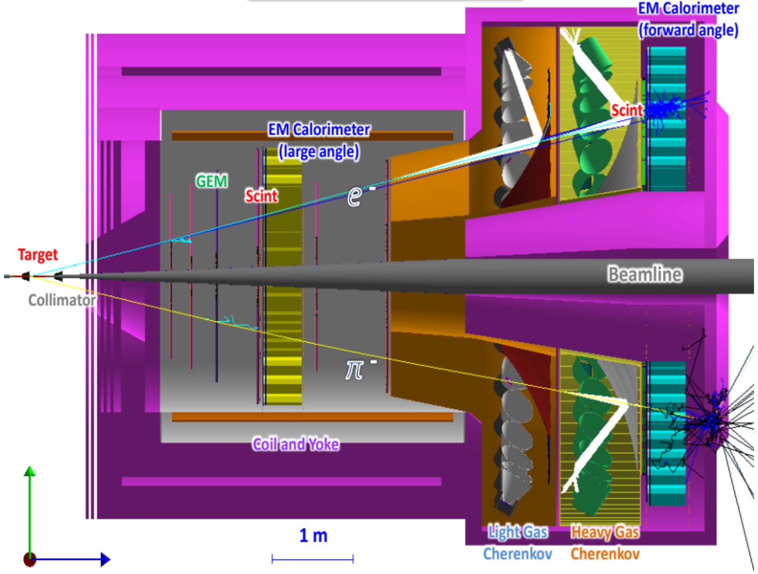






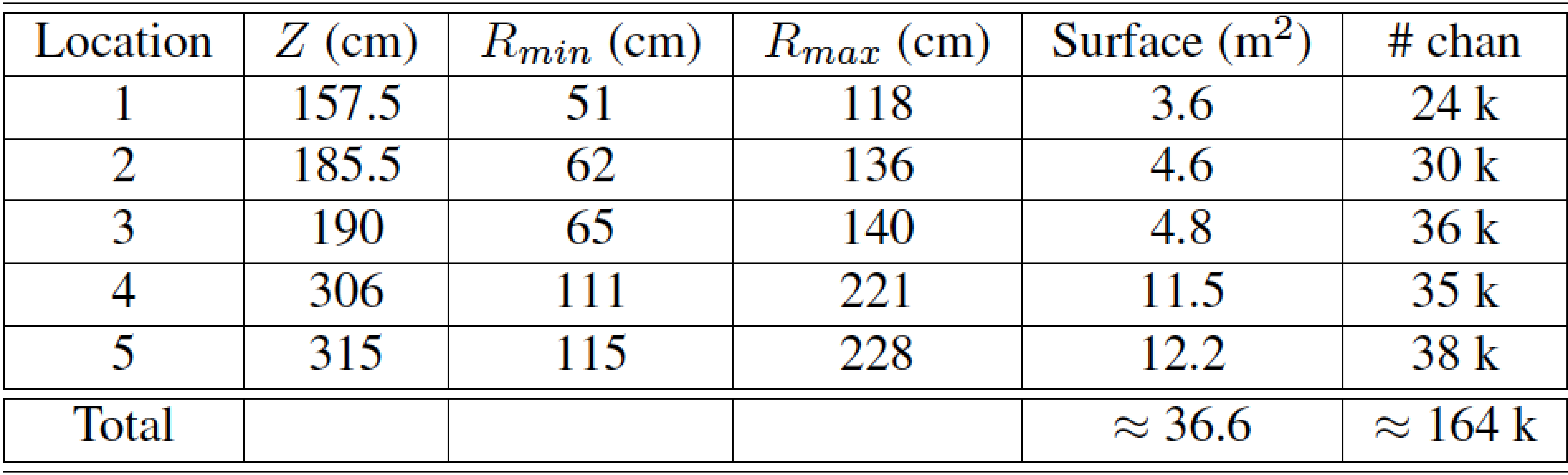


SoLID (SIDIS and J/ψ)



MPGDs in Hall A @ JLab: SoLID GEM requirements for PVDIS

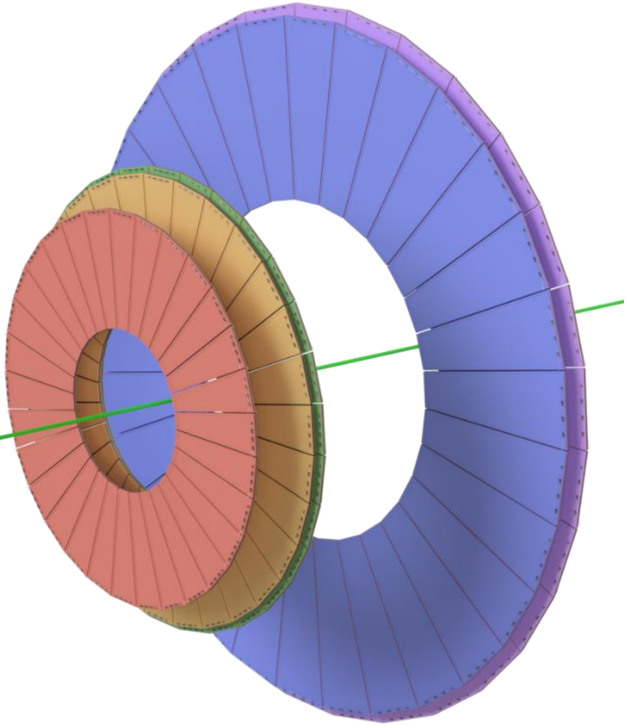
- ❑ High rate operation up to localized hit rates of approximately 1 MHz/cm^2.
- ❑ Instrument 5 locations with GEMs:
  - ❑ 30 GEM modules a location: each module with a 12-degree angular width.



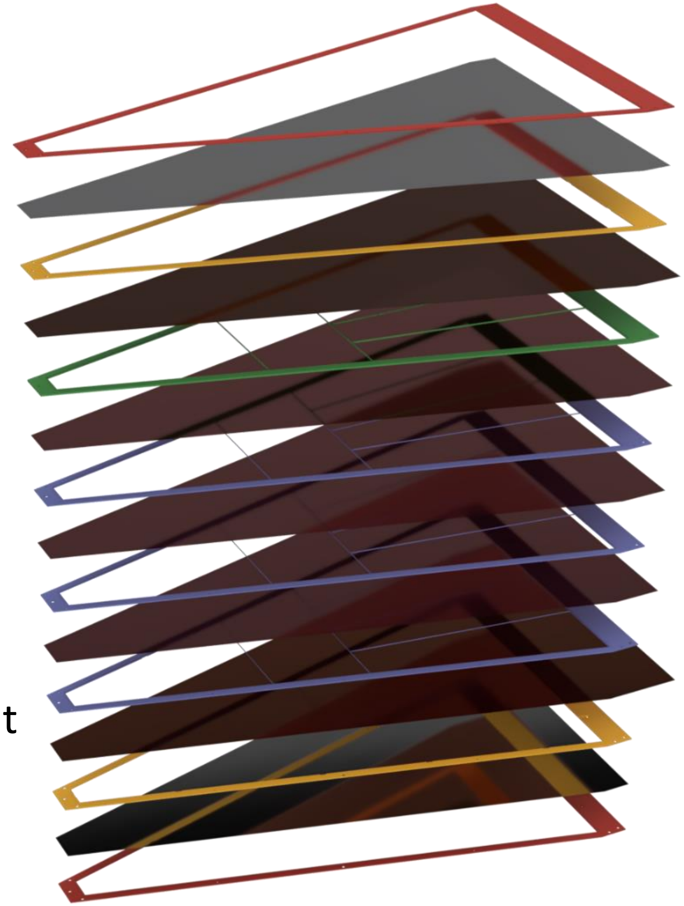
Location	Z (cm)	R_{min} (cm)	R_{max} (cm)	Surface (m^2)	# chan
1	157.5	51	118	3.6	24 k
2	185.5	62	136	4.6	30 k
3	190	65	140	4.8	36 k
4	306	111	221	11.5	35 k
5	315	115	228	12.2	38 k
Total				$\approx$ 36.6	$\approx$ 164 k

- ➢ The high occupancy at layer #1: may require splitting each readout strip into two channels: this will add another 12 k channels
- ➢ So, total number of channels needed could be : ~ 176 k
- ➢ With ~ 15% spares (to account for losses during production etc.) need to plan for 200 k readout channels
- ➢ Lot of data at high occupancy; but we can have multiple parallel DAQs

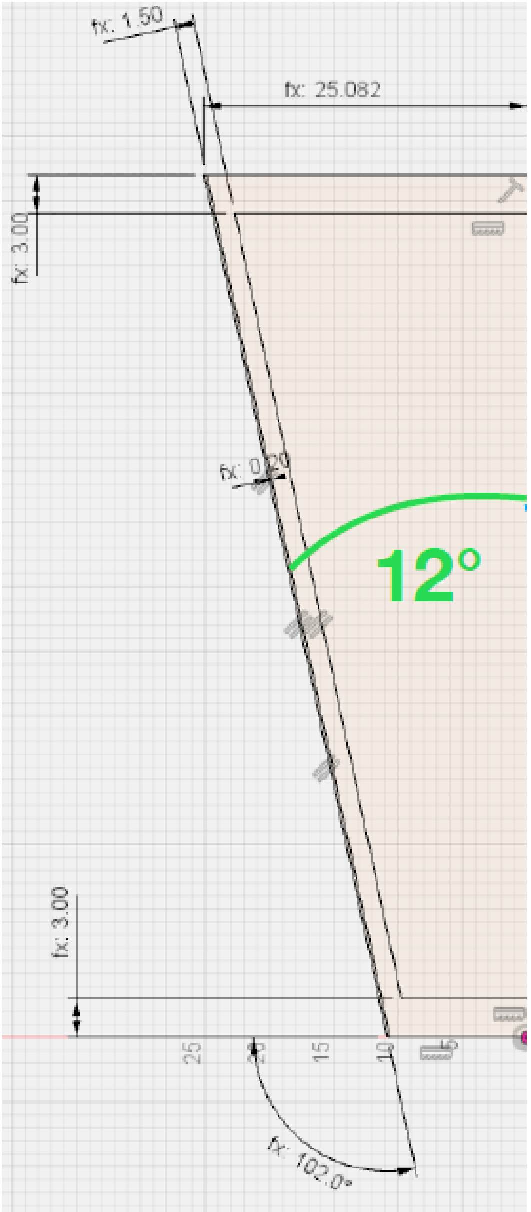
MPGDs in Hall A @ JLab: SoLID GEM Design



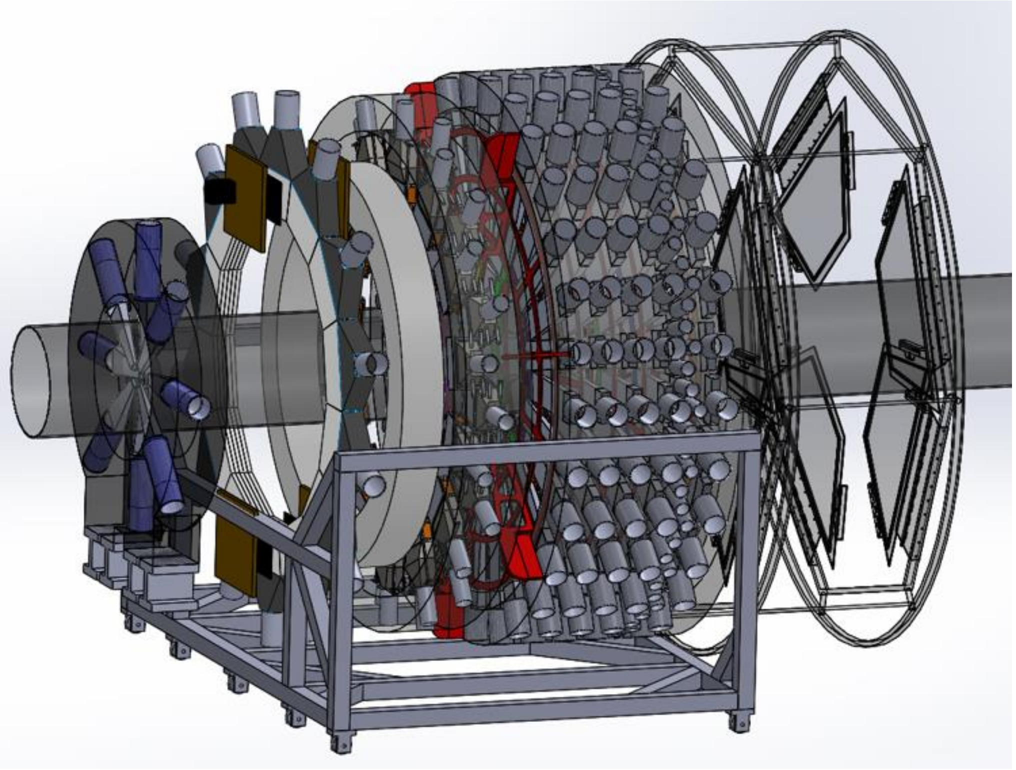
PVDIS GEM tracker arrangement

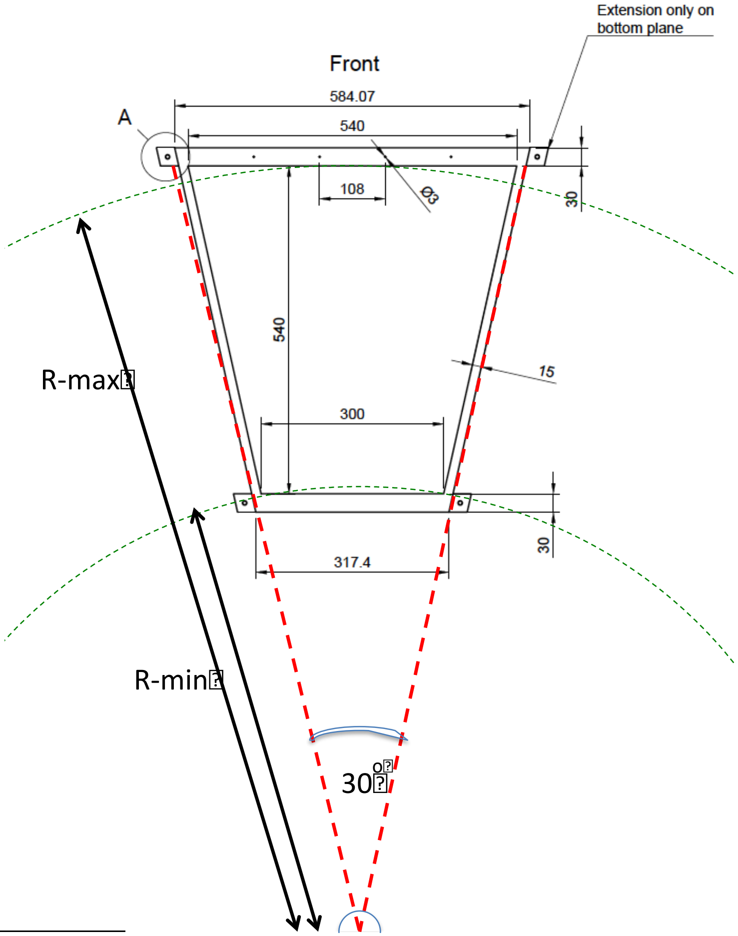


CNC-ready CAD design for a single GEM module for SoLID.



MPGDs in Hall A @ JLab: Moller GEM





	z(m)	Inner rad(m)	Outer rad(m)	$\pm\phi$(deg)
GEM #1	19.25	0.54	1.08	31.0
GEM #2	19.75	0.56	1.10	30.5
GEM #3	21.0	0.58	1.12	28.8
GEM #4	21.5	0.59	1.13	28.8

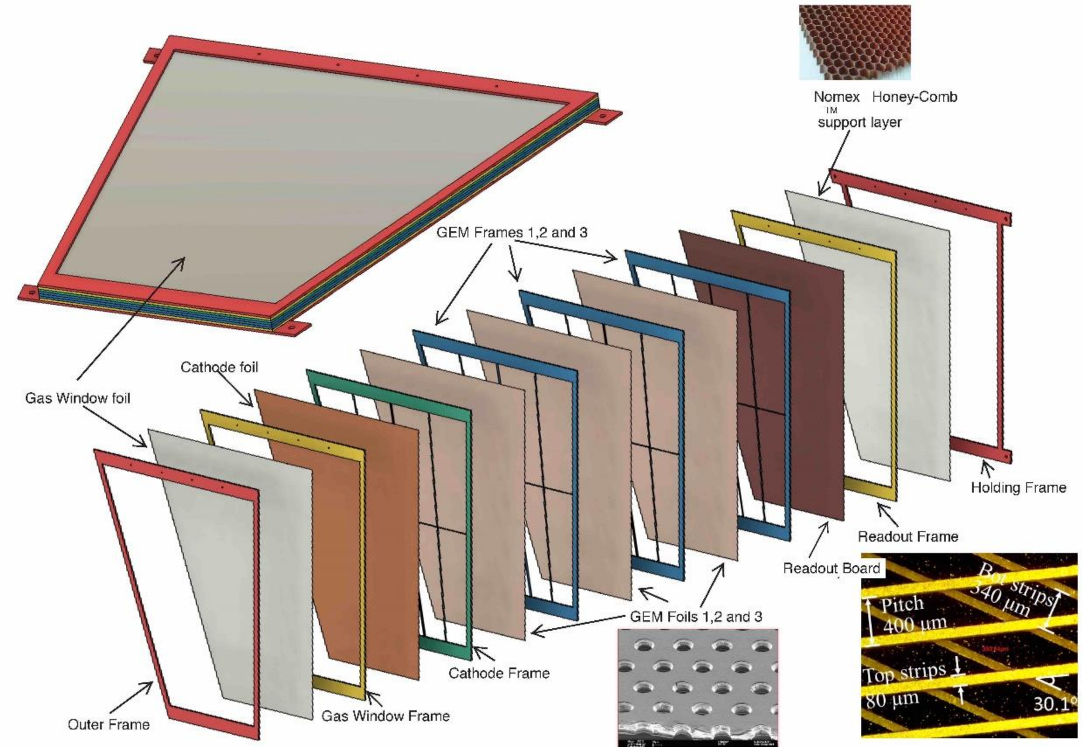
Sizes are close enough;

So one size fits all

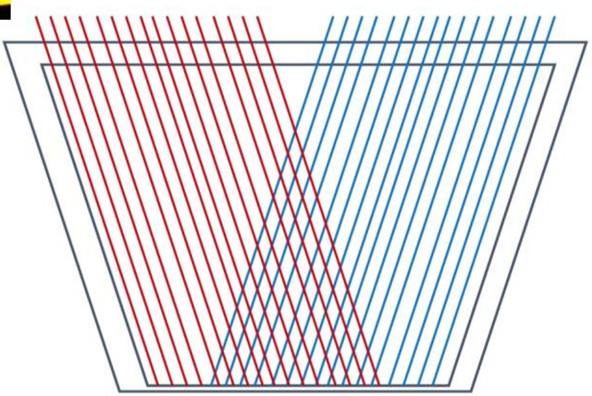
Convenient for

- construction
- spares

MPGDs in Hall A @ JLab: Moller GEM

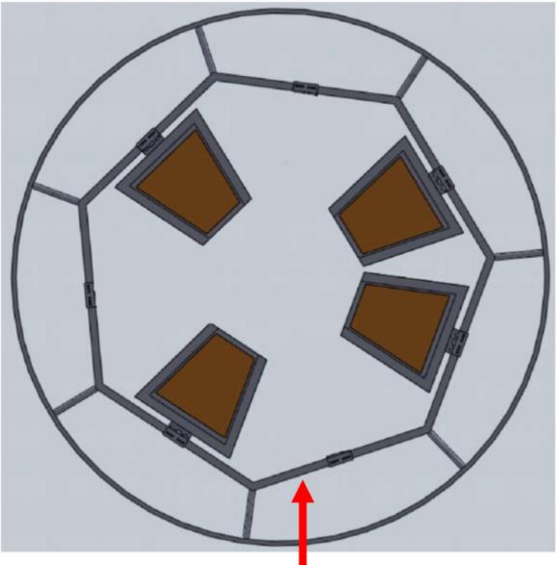


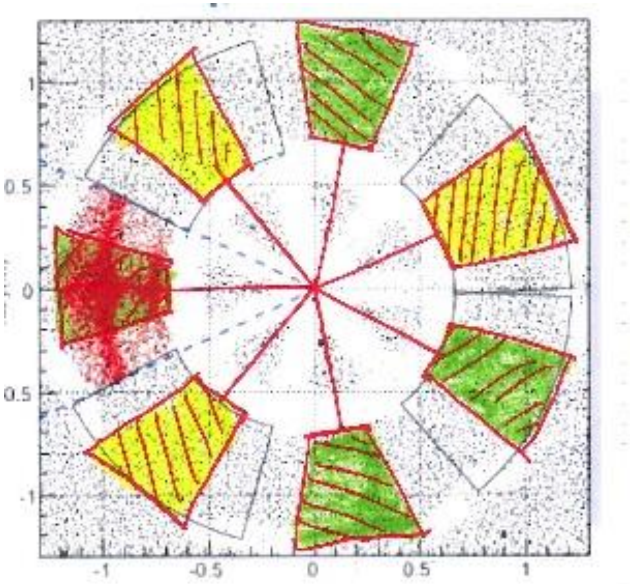
- ☐ 800 micron pitch in each direction
- ☐ All readout from outer edge
- ☐ 26-degree stereo angle
- ☐ sub-mm resolution in both R and phi
- ☐ ~ 1300 channels per module



MPGDs in Hall A @ JLab: Moller GEM

- 4 Layers: Require 4 (x,y,z) points per track: 3 to give a χ^2 criterion, one to allow for inefficiency
- Rotatable: cover full azimuthal acceptance in several measurements
- GEMs removable (“flap” out of acceptance) for asymmetry measurement (can’t tolerate backgrounds from frames) Scintillators removable
- Cover at least one section with two different sets of GEM modules, to confirm GEM efficiency properly accounted for

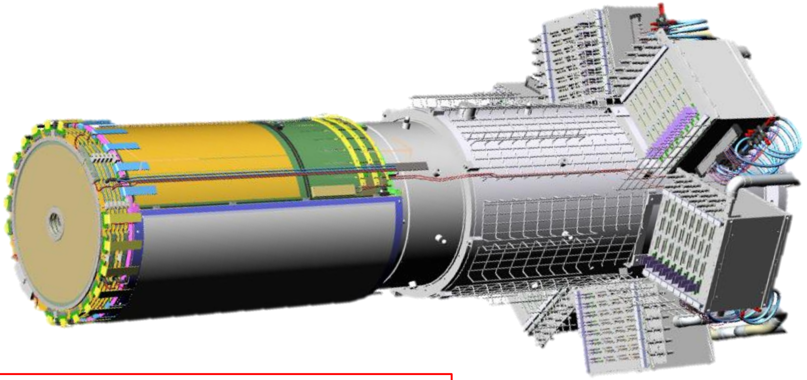




MPGDs @ JLab

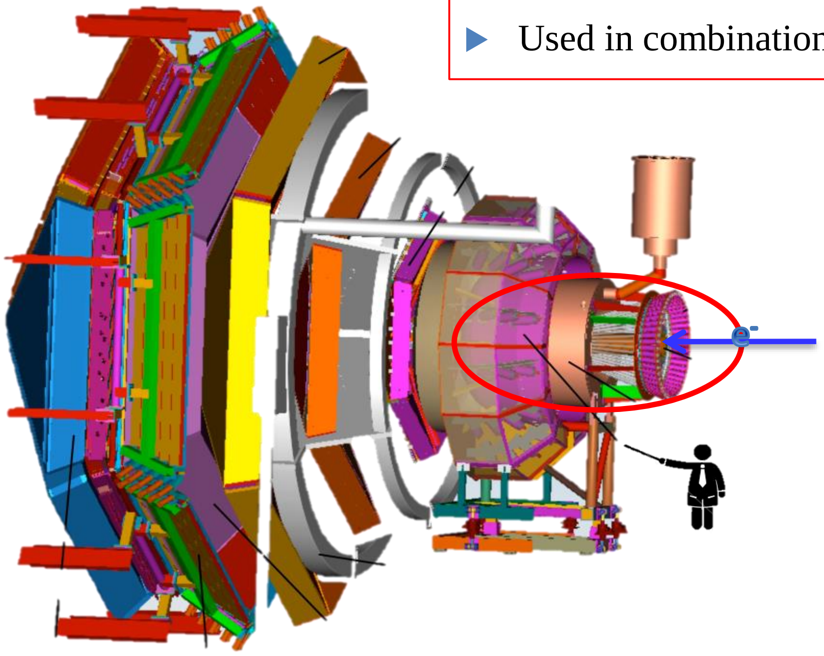
MPGDs elsewhere @ JLab: CLAS12 μMegas Vertex Trackers (MVTs)

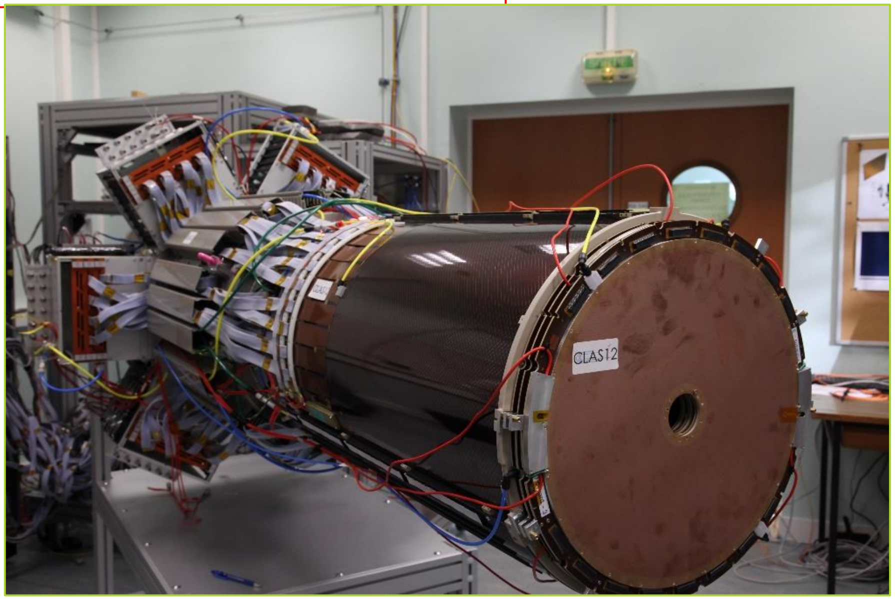
- Upgrade of the CLAS Experiment at Jefferson lab
- Study of the nucleon structure with ~11 GeV electron beam at high luminosity (10^{35} cm^{-2}s^{-1})
- Targets : liquid hydrogen (protons), liquid deuterium (neutrons), other nuclei in the future



Micromegas Vertex Tracker (MVT) :

- Improve the track reconstruction in the vicinity of the target
- Inserted in the 5T solenoid
- Used in combination with the Silicon Vertex Tracker (SVT)

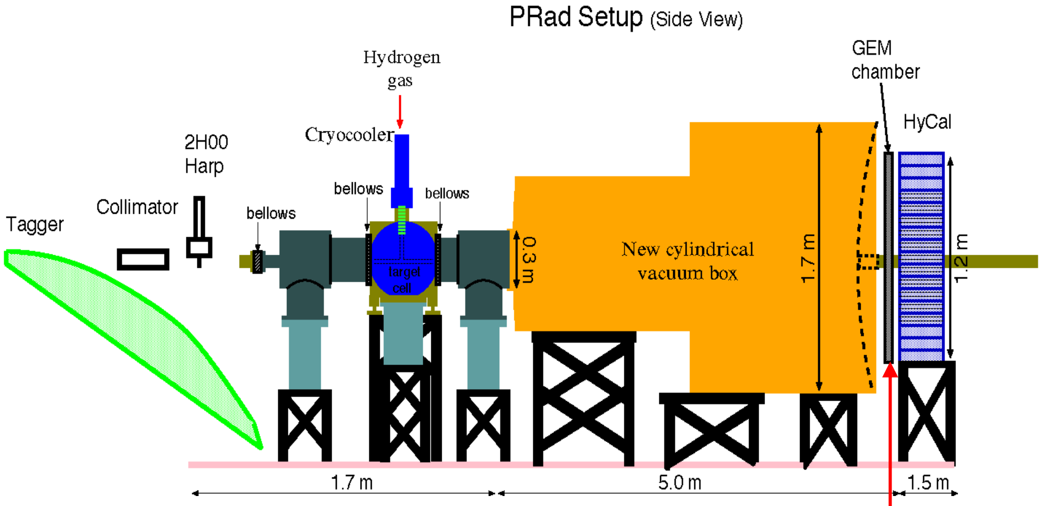


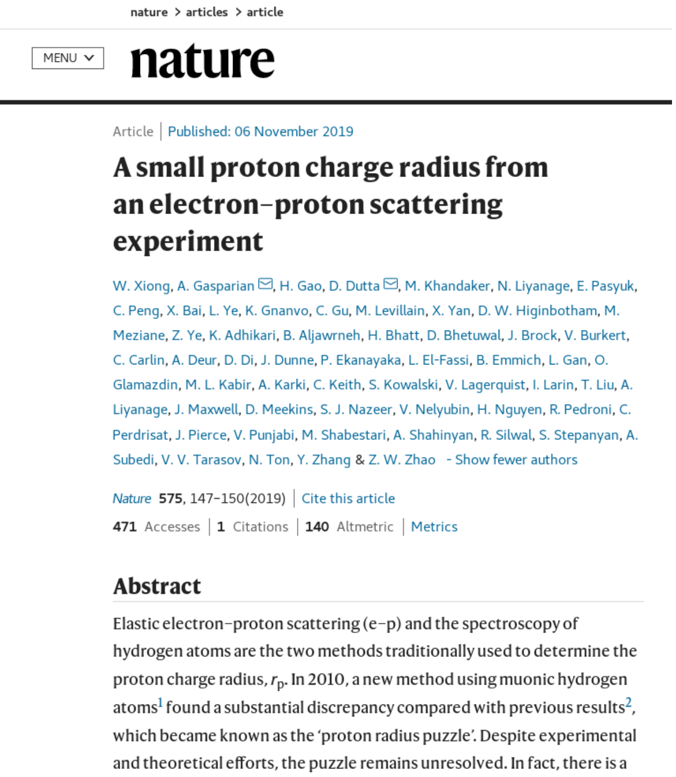


MPGDs elsewhere @ JLab: PRad Large GEMs

PRad Experiment in Hall B (Summer 2016):

- Measure proton charge radius using ep elastic scattering
- Covers two orders of magnitude in low Q^2 with the same detector setting $(\sim 2 \times 10^{-4} – 6 \times 10^{-2}\ \mathrm{GeV}^2)$
- Unprecedented low Q^2 $(\sim 2 \times 10^{-4}\ \mathrm{GeV}^2)$
- Normalize to the simultaneously measured Møller scattering process to control systematics
- Extract the radius with precision from sub-percent cross section measurement

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nature

Article | Published: 06 November 2019

A small proton charge radius from an electron–proton scattering experiment

W. Xiong, A. Gasparian, H. Gao, D. Dutta, M. Khandaker, N. Liyanage, E. Pasyuk, C. Peng, X. Bai, L. Ye, K. Gnanvo, C. Gu, M. Levillain, X. Yan, D. W. Higinbotham, M. Meziane, Z. Ye, K. Adhikari, B. Aljawrneh, H. Bhatt, D. Bhetuwal, J. Brock, V. Burkert, C. Carlin, A. Deur, D. Di, J. Dunne, P. Ekanayaka, L. El-Fassi, B. Emmich, L. Gan, O. Glamazdin, M. L. Kabir, A. Karki, C. Keith, S. Kowalski, V. Lagerquist, I. Larin, T. Liu, A. Liyanage, J. Maxwell, D. Meekins, S. J. Nazeer, V. Nelyubin, H. Nguyen, R. Pedroni, C. Perdrisat, J. Pierce, V. Punjabi, M. Shabestari, A. Shahinyan, R. Silwal, S. Stepanyan, A. Subedi, V. V. Tarasov, N. Ton, Y. Zhang & Z. W. Zhao - Show fewer authors

Nature **575**, 147–150(2019) | Cite this article

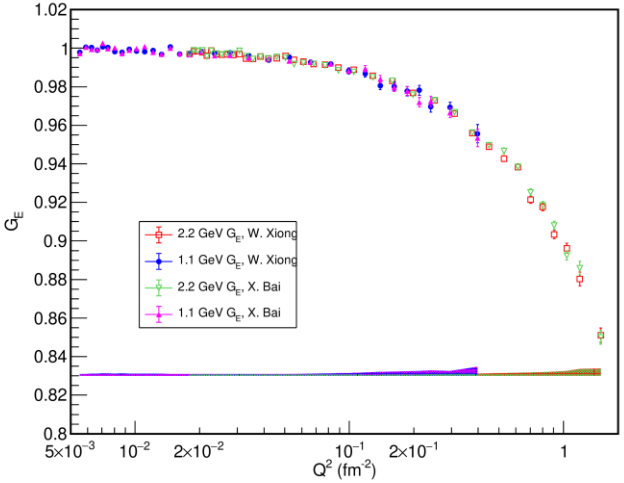
471 Accesses | **1** Citations | **140** Altmetric | Metrics

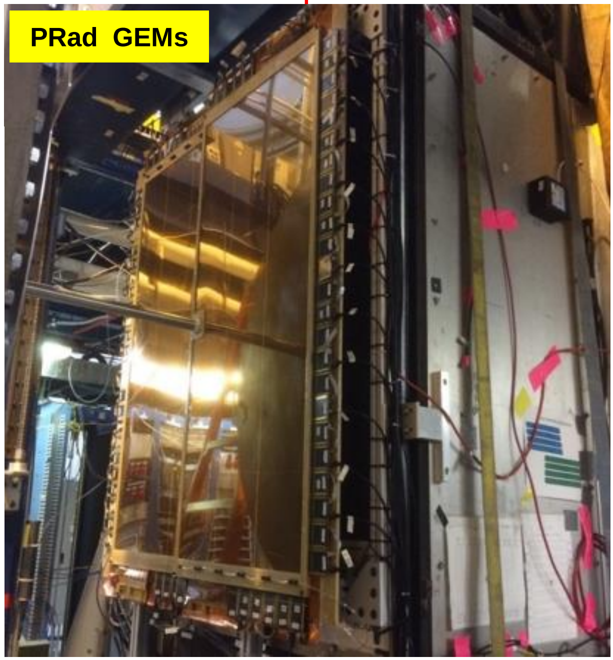
Abstract

Elastic electron–proton scattering (e–p) and the spectroscopy of hydrogen atoms are the two methods traditionally used to determine the proton charge radius, r_p. In 2010, a new method using muonic hydrogen atoms[1] found a substantial discrepancy compared with previous results[2], which became known as the 'proton radius puzzle'. Despite experimental and theoretical efforts, the puzzle remains unresolved. In fact, there is a

- Two large area GEM detectors
- Small overlap region in the middle
- Excellent position resolution (72 μm)
- Improve position resolution by > 20 times
- Large improvement for Q^2 determination

Extracted G_E from two analysis





MPGDs for EIC

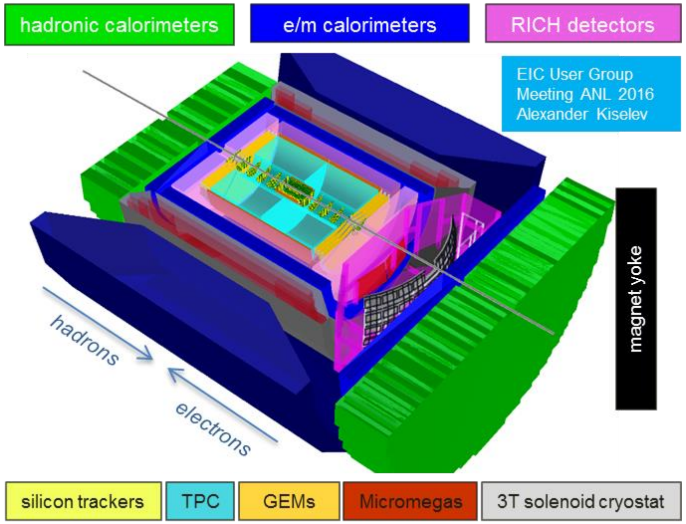
MPGDs for the future Electron Ion Collider (EIC)

BNL, in association with Jefferson Laboratory and the DOE Office of Nuclear Physics, has established a **generic EIC detector R&D program** to address the requirements for measurements at a future Electron Ion Collider (EIC).

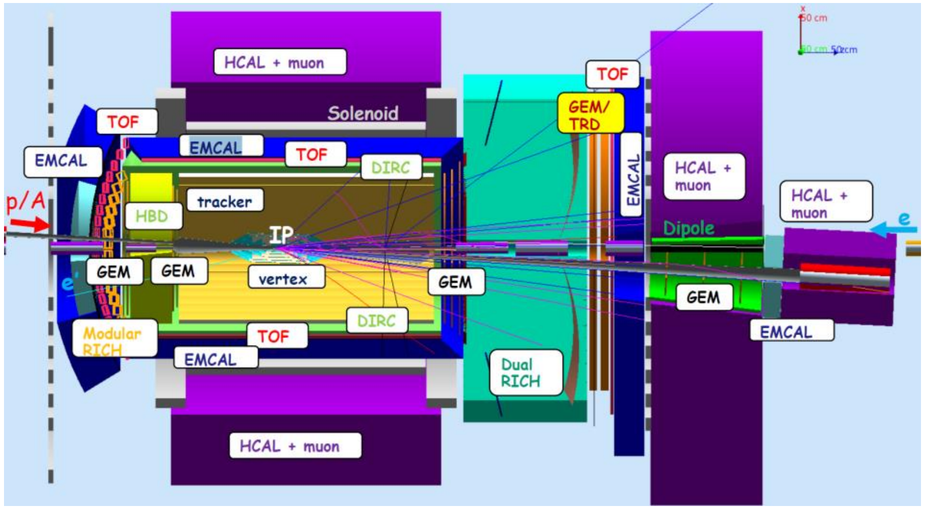
Some of the ongoing R&D on MPGD for the EIC detector (eRD6 / eRD3 / eRD22)

- GEM, µMegas & µRWELL amplification and readout structure for TPC **(BNL, Yale U.)**
- Cylindrical µRWELL for the Central Tracker **(Florida Tech, UVa, Temple U.)**
- Planar Large area GEM for the End Cap Tracker **(Florida Tech, UVa, Temple U.)**
- Hybrid THGEM + µMegas for RICH detector application **(INFN Trieste)**
- GEM readout for short radiator length RICH and Ion Back flow Structures; **(SBU)**
- 3-D-coordinate readout for GEMs; **(Yale Univ.)**
- GEM-based Transition Radiation Detector for e-PID **(JLab, UVa, Temple U.)**

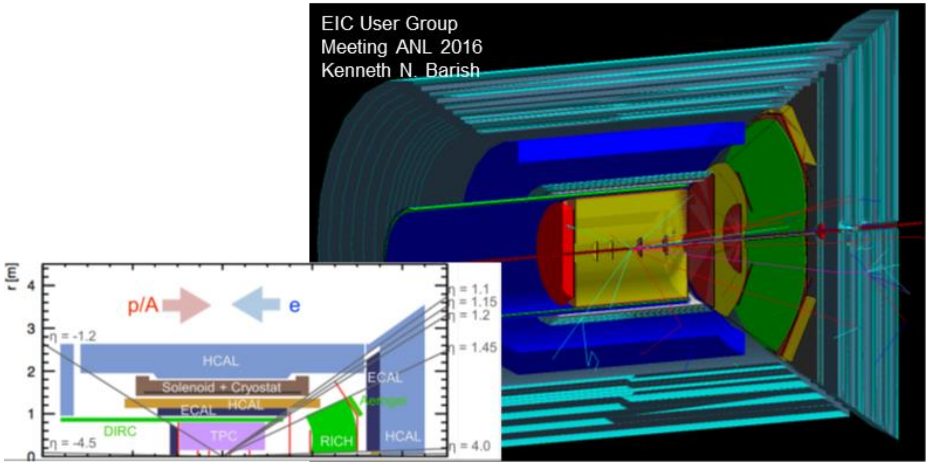
BeAST @ eRHIC



EIC Detector Concept (JLEIC) Design

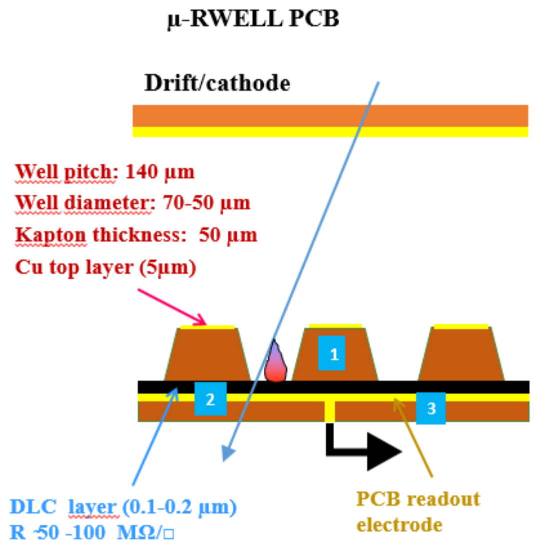


ePHENIX @ eRHIC

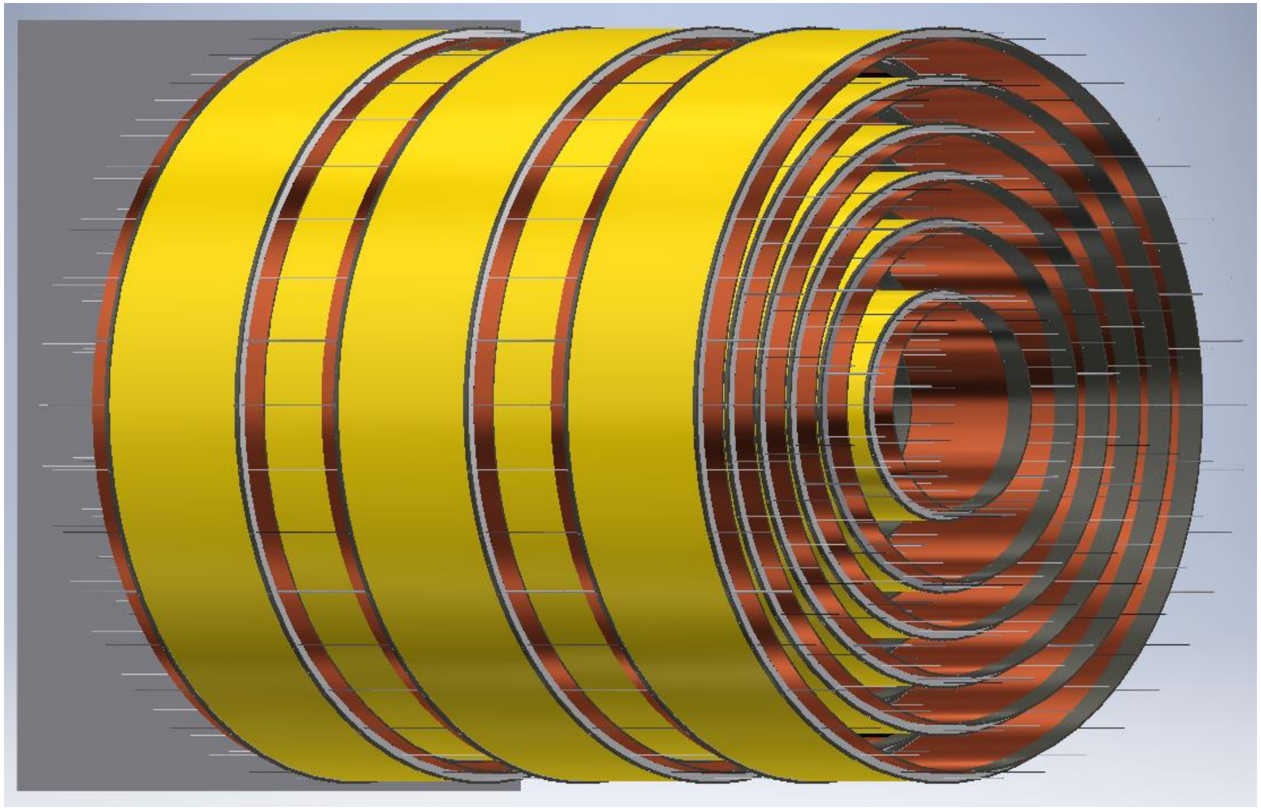


MPGDs for EIC: Barrel Tracking detector

Conceptual Design Studies - Cylindrical μRWELL for EIC Barrel Tracker



G. Bencivenni et al., 2015_JINST_10_P02008



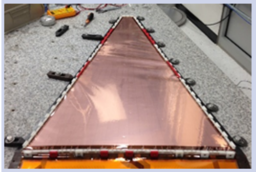
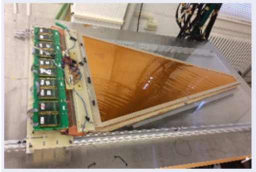
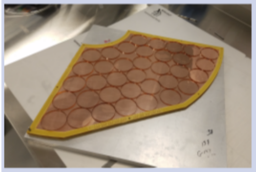
Florida Tech, Temple U., UVa

MPGDs for EIC: End Cap Tracking detector

Development of large area & low-mass triple GEM detector for the end cap tracker of an EIC

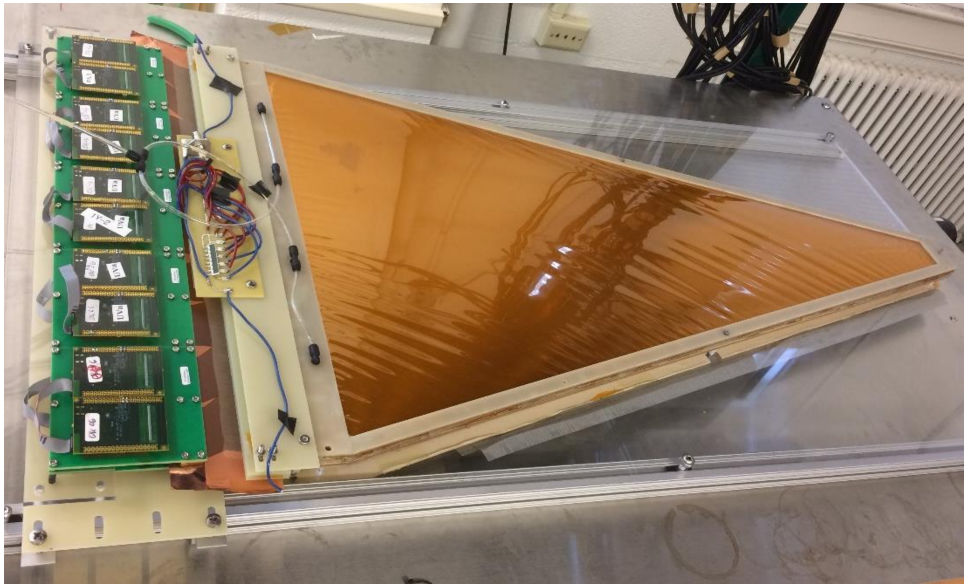
- Three Institutes: Florida tech; Temple U, and UVa
- 3 different approaches for the assembly techniques, readout strip pattern …
- Prototypes build and tested at Fermilab

EIC End Cap Trackers GEM development share a lot of similarities with SoLID GEM Trackers

	Status of the prototype	Assembly technique	Readout technology	spatial resol (phi × Rphi)	Low mass	Dead area from support frames	Dead area in active area	FE cards connection
FIT FT-GEM 	Assembled – Technical issues – Fixes underway X	**Mech. Stretching technique - chamber can be reopened √**	1D Zigzag strips X	100 µm √ **but 1D only**	**Yes √**	Carbon Fiber, G10 Fiber glass, metallic piece X	**No spacers √**	Standard - Outside active area √
UVa FT-GEM 	**Assembled – Tested in beam at FNAL √**	Glued frames - chamber can't be reopened X	**2D U-V stereo-angle strips √**	100 µm × 500 µm √	**Yes √**	**Fiber glass (G10) 15 mm √**	300 µm straight spacers grid X	**Zebra - Outside active area √**
TU FT-GEM 	STAR FGT Technical issues – Fixes underway X	Glued frames - chamber can't be reopened X	**2D radial-Azimuth strips √**	**100 µm × 100 µm √**	**Yes √**	(G10) 15 mm but FE cards on the side X	50 µm Kapton rings X	Outside active area But FE on side X ?

Florida Tech, Temple U., UVa

MPGDs for EIC: End Cap Tracking detector

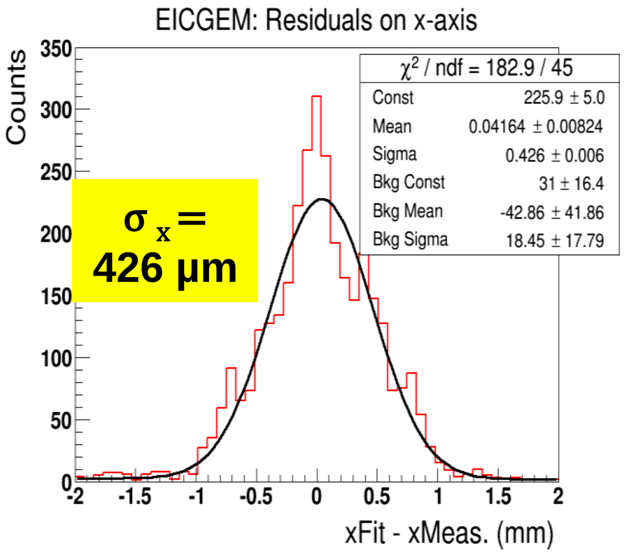


UVa Prototype:

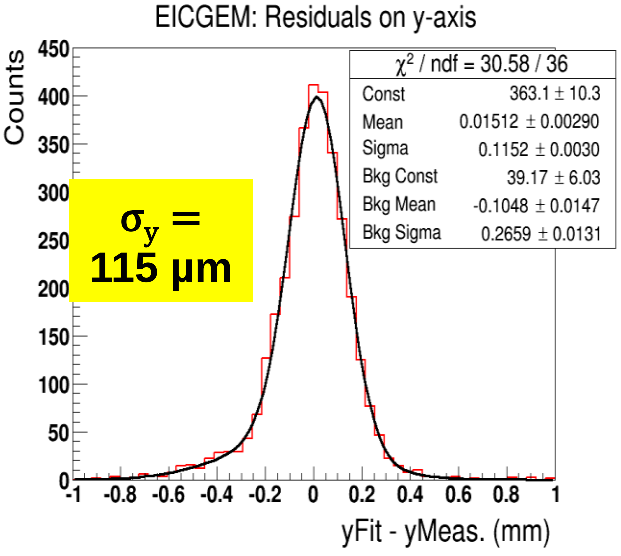
Implement several new ideas that will benefit MOLLER & SoLID GEMs

- U-V strip readout with excellent spatial resolution performances
- Low-mass detector: All foils in active area ⇨ no rigid PCB support
- Zebra connectors scheme ⇨ concentrations of FE electronics on one side of the detectors

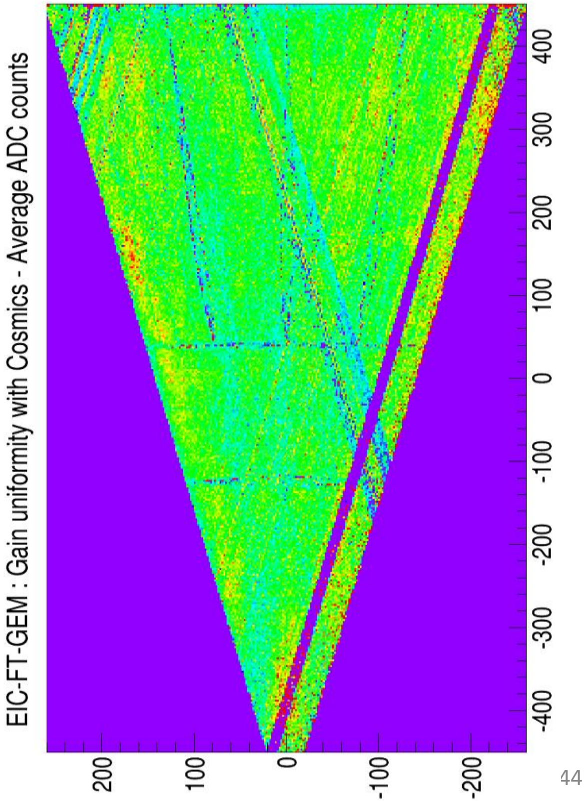
Spatial resolution of the detector with U-V strip readout



$\sigma_x =$ 426 μm



$\sigma_y =$ 115 μm



MPGDs for EIC: Hybrid MPGDs for RICH Detectors

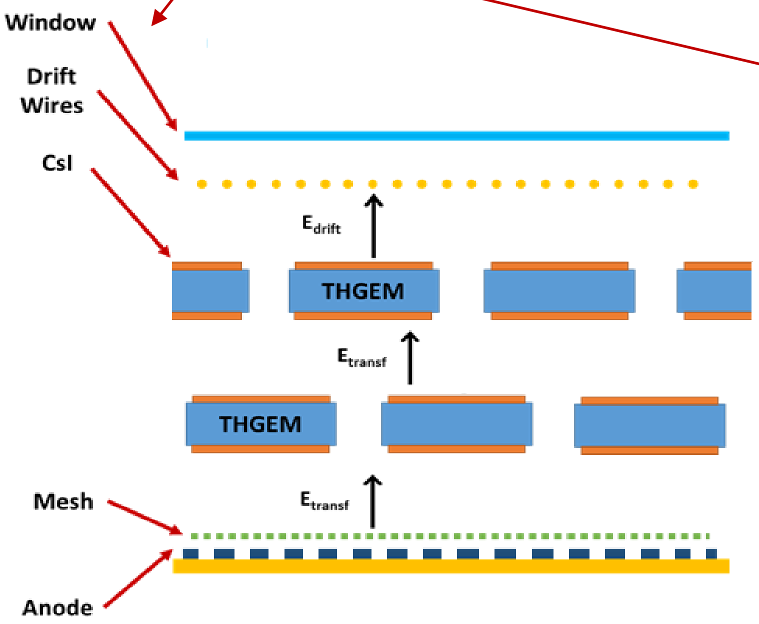
R&D for MPGD-based photodetectors @ INFN Trieste :

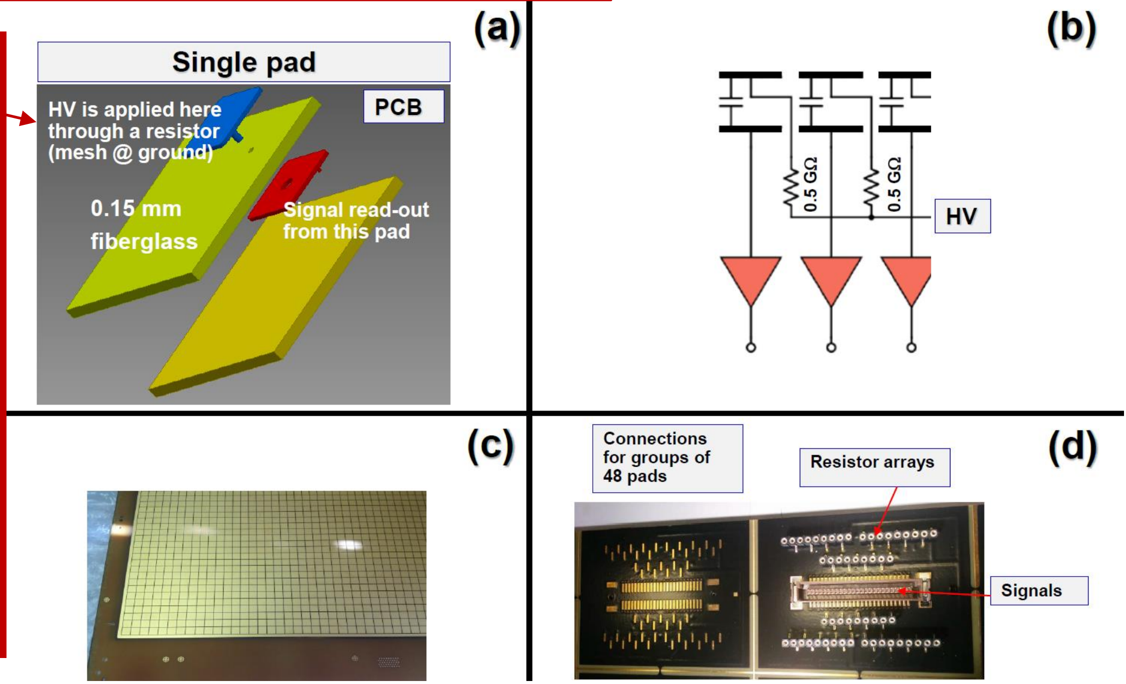
Scheme: hybrid MPGDs (= 2 (TH)GEMs + 1 MICROMEGAS, 3 stages in total) MPGD for single photon detection for

- PID, in particular high momentum RICHes
- Synergies with TPC sensors by MPGD technologies

The starting status (COMPASS RICH upgrade):

- *Scheme of the detector architecture*
- *The resistive anode by discrete elements*





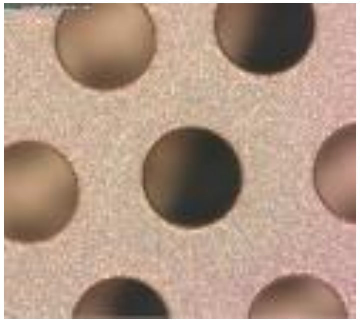
MPGDs for EIC: MPGDs for RICH Detectors

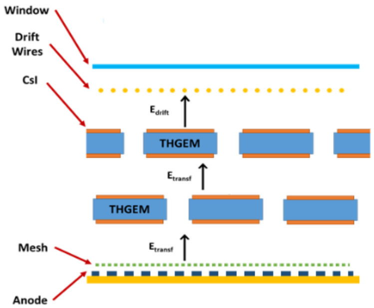
Thick GEMs for COMPASS RICH1 PD Upgrade:

MWPCs replaced by THGEMs + CsI + Micromegas

Typical PARAMETERS:

- ⇨ Diam. = 0.4 mm, Pitch = 0.8 mm
- ⇨ Thick. = 0.4 mm, Rim = 10 µm
- ⇨ Fast signal (ns), Gain @ HV = 2kV: 10^5 atmospheric pressure



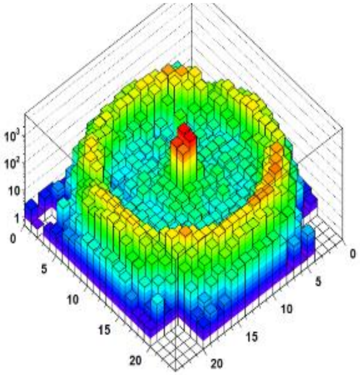


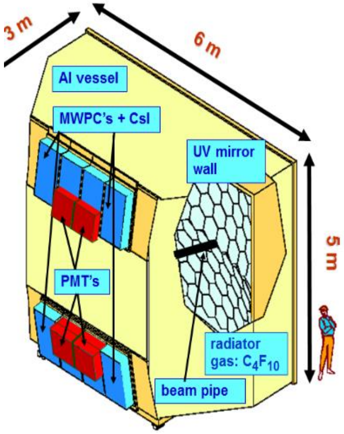
R. Chechik, A. Breskin, C. Shalem

GEM-like multipliers for large area UV-RICH detectors

- ⇨ PCB Etching and drilling
- ⇨ Simple and robust & cost effective

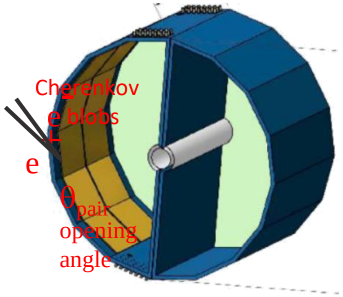
Ring reconstruction

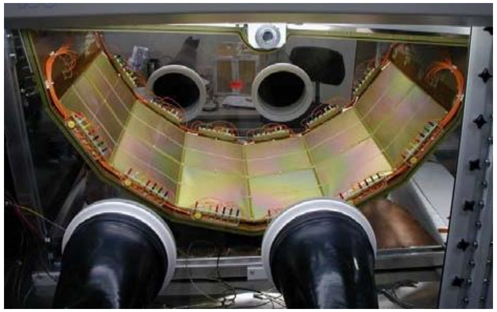


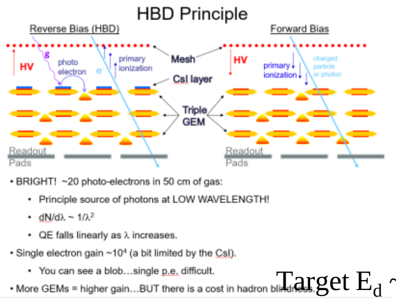


F. Tessaroto, MPGD2015, Trieste, Italy, 10/12/2015

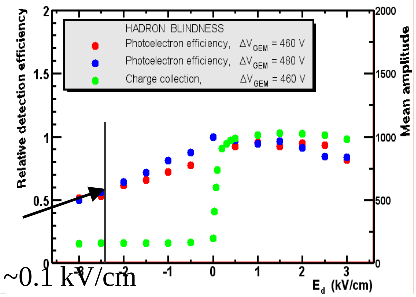
Hadron Blind Detector (HBD), PHENIX @ BNL







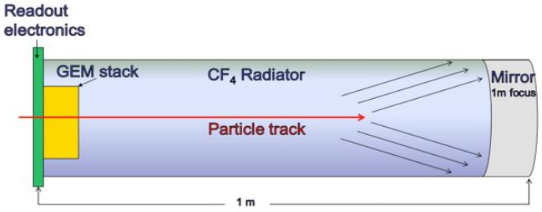
- BRIGHT! ~20 photo-electrons in 50 cm of gas:
  - Principle source of photons at LOW WAVELENGTH!
  - $dN/d\lambda \sim 1/\lambda^2$
  - QE falls linearly as λ increases.
- Single electron gain $\sim 10^4$ (a bit limited by the CsI).
  - You can see a blob…single p.e. difficult.
- More GEMs = higher gain…BUT there is a cost in hadron blindness.

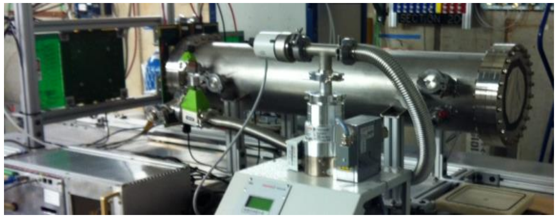


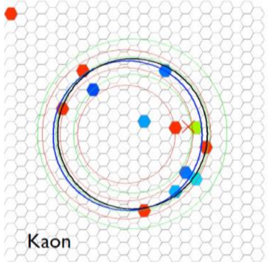
Target E_d ~0.1 kV/cm

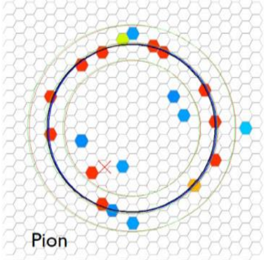
T. Hemmick, SoLID Coll. Meeting @ JLab 02/03/2012

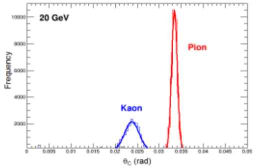
HBD-like RICH (Generic R&D)

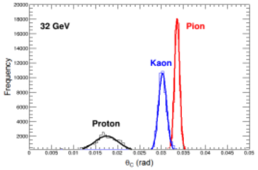












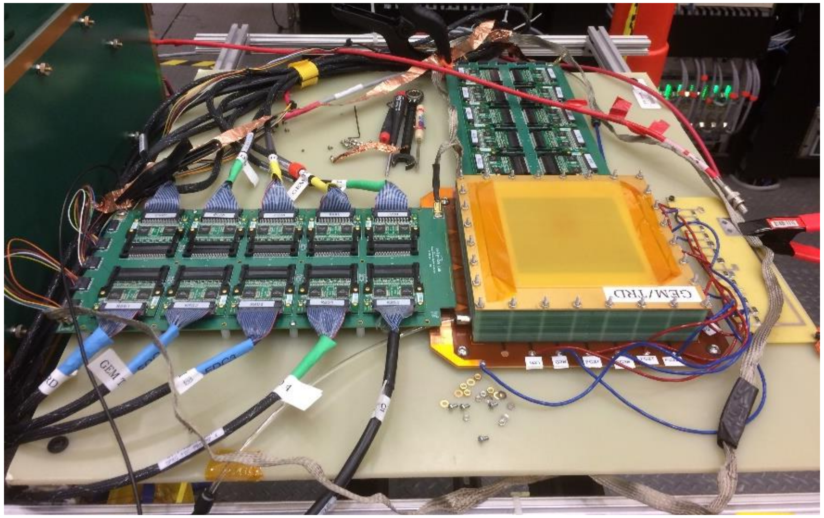
T. Hemmick, MPGD 1017, Temple Univ., 05/23/2017

MPGDs for EIC: GEM Transition Radiation Detector (GEM-TRD)

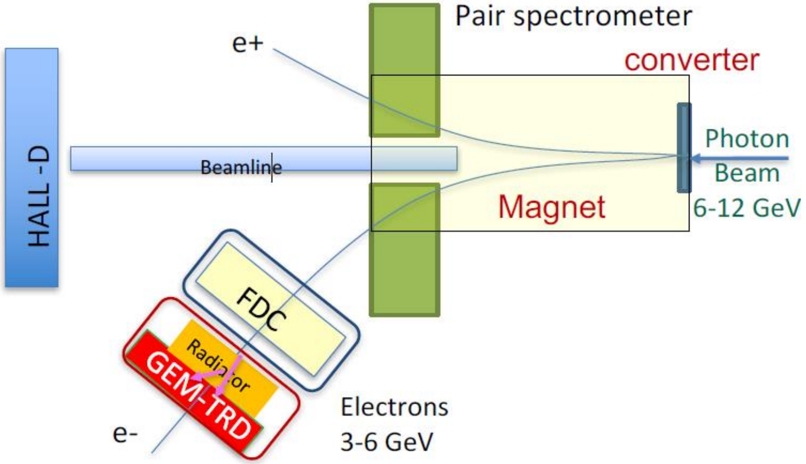
eRD22 is an EIC Detector R&D program to develop GEM-based Transition Radiation Detector for Electron ID in the hadron endcap

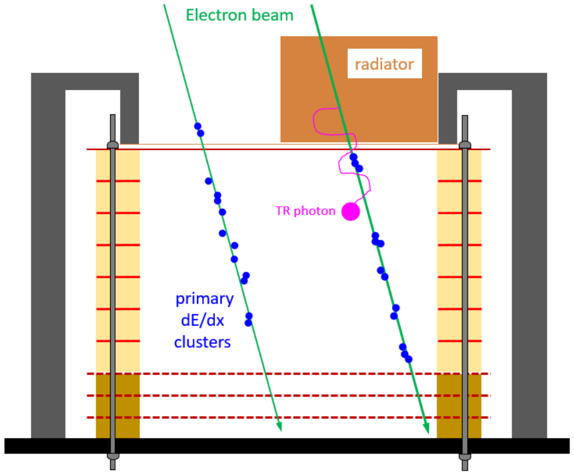
eRD22 Team: **JLab:** Y. Furletova, S. Furletov, L. Pentchev, H. Fenker, B. Zihlmann, C. Stanislas, F. Barbosa; **University Of Virginia :** K. Gnanvo, N. Liyanage; **Temple University :** M. Posik, B. Surrow

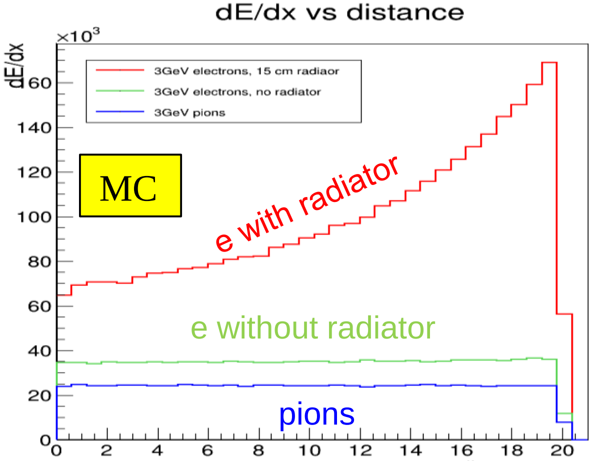
GEM-TRD prototype with JLab F125 Electronics

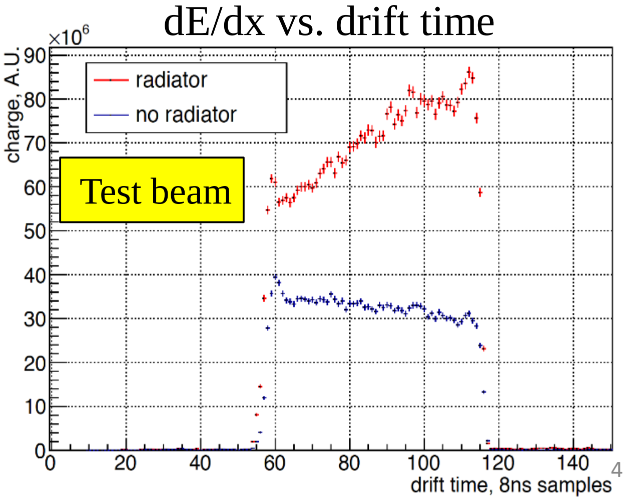


Prototype in Test Beam in Hall D





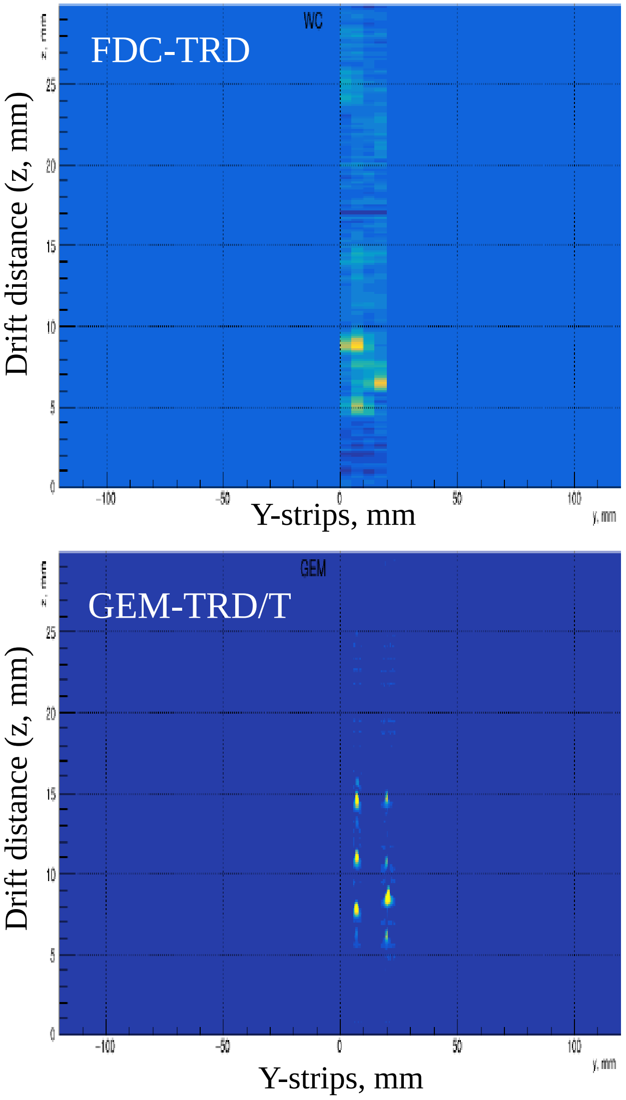




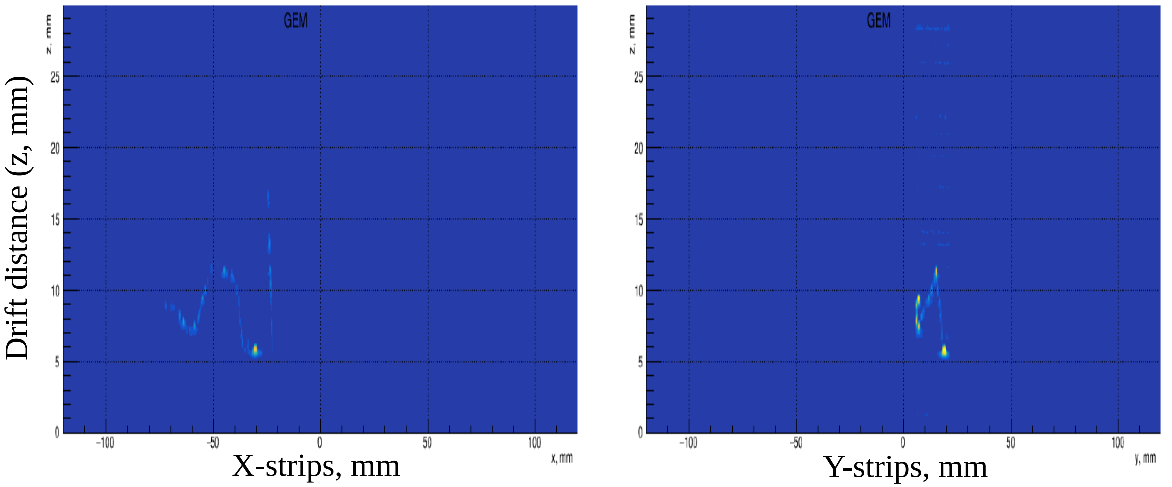
MPGDs for EIC: GEM-TRD & Tracking

GEM-TRD will provide additional precise tracking information (in µTPC mode) in addition to the Electron ID

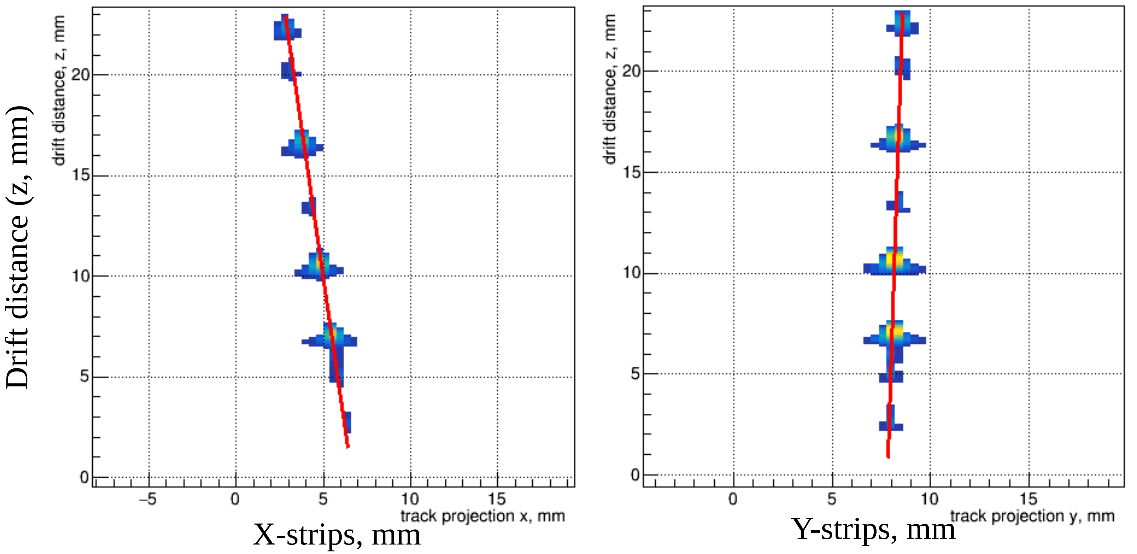
Two tracks event



Event with delta electron track in GEM-TRD/T



Tracks from clusters separation (µTPC mode)

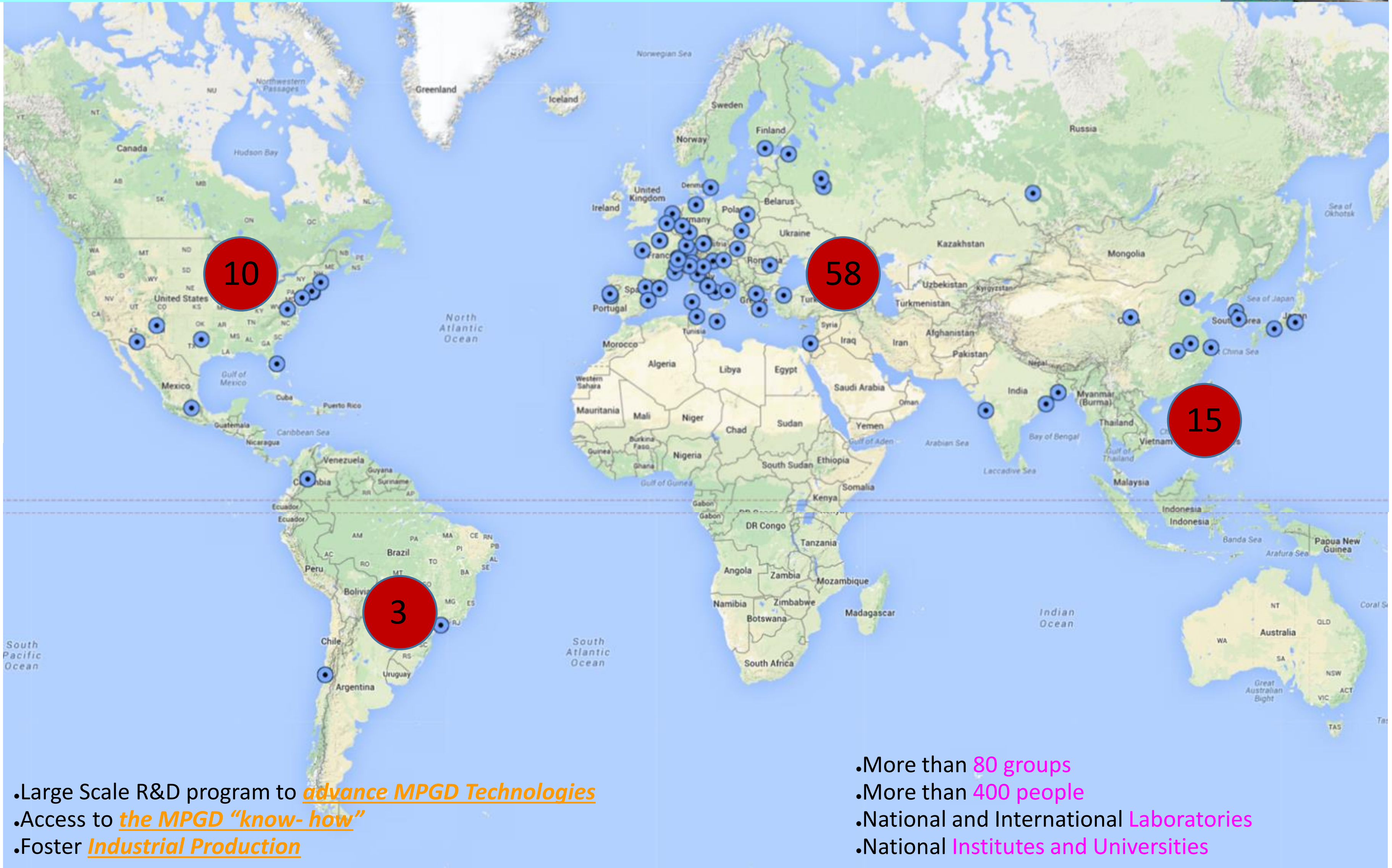


Back-up

RD51 Collaboration @ CERN

RD51: Based @ CERN but Not a CERN-only collaboration

The main objective: advance MPGD technological development & associated electronic-readout systems, for applications in basic and applied research”
http://rd51-public.web.cern.ch/rd51-public

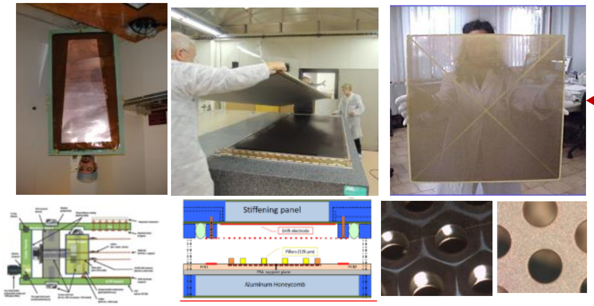


- Large Scale R&D program to ***advance MPGD Technologies***
- Access to ***the MPGD “know- how”***
- Foster ***Industrial Production***

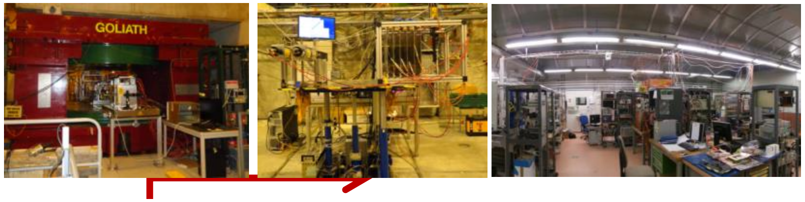
- More than 80 groups
- More than 400 people
- National and International Laboratories
- National Institutes and Universities

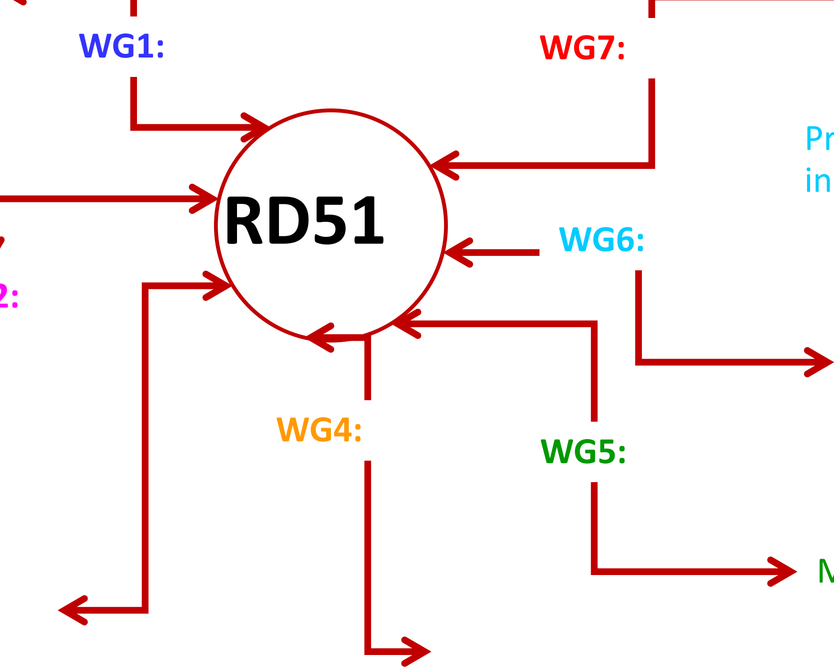
RD51: Working Groups

Technological Aspects and Development of New Detector Structures



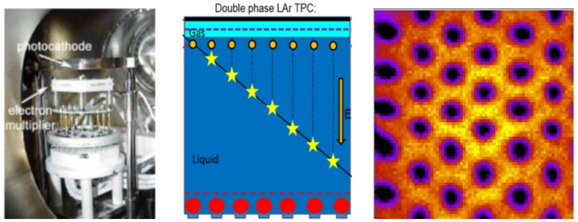
Common Facilities : Test Beam and Laboratory



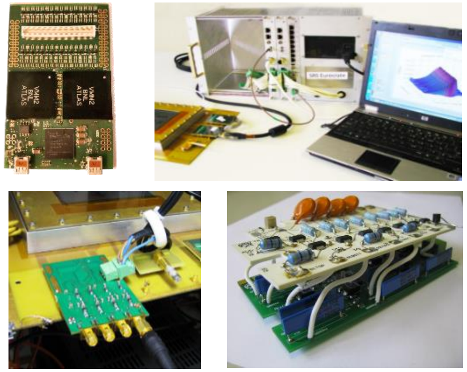


Production, quality control, industrialization

Common Characterization and Physics Issues



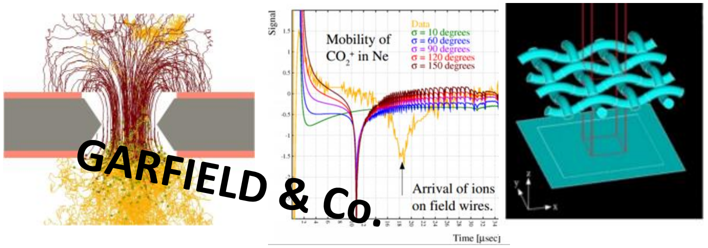
MPGD readout Electronics



WG3/NEW WG:

Academia-Industry Matching Events, Training, Education

Simulations and Software Tools



RD51: Achievements

- Consolidation of the Collaboration and MPGD community integration (>80 Institutes, >400 members);
  - WORLWIDE DISSEMINATION and large support to NEW COMMUNITIES
  - ACADEMIA-INDUSTRY MATCHING EVENTS
  - TRAINING & SCHOOLS

- Major progress in the MPGD technologies development in particular large area GEM (single mask), MicroMegas (resistive), THGEM; some picked up by experiments (including LHC upgrades);
  - MPGD selected for HEP & NP experiments as a result of these major progresses.
  - PHASE-DRIVEN (R&D or production) SUPPORT
  - NEW REQUIREMENTS (future experiment driven) and NEW AREA of USE

- Secured future of the MPGD technologies development through the TE MPE workshop upgrade and FP7 AIDA contribution;
  - CERN MICRO PATTERN TECHNOLOGY WORKSHOP scaled up to SQUARE METERS detector size

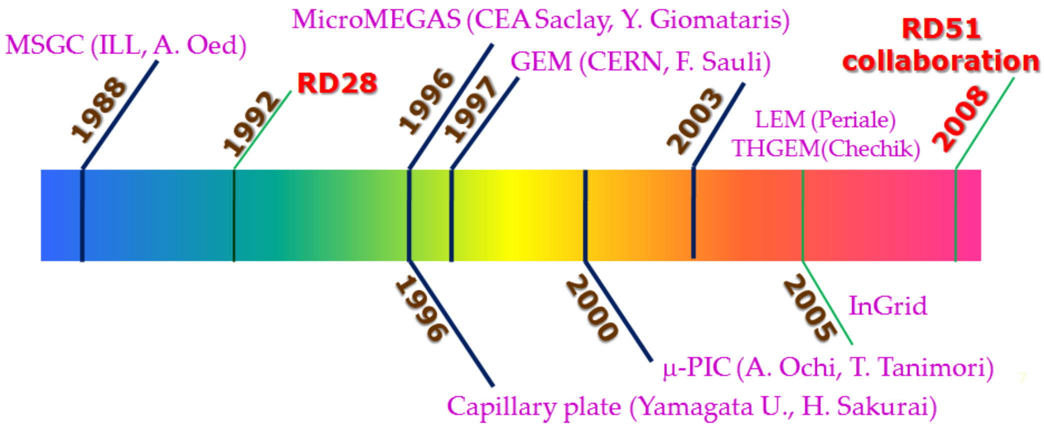
- Contacts with industry for large volume production, MPGD industrialization and industrial runs;
  - CONSOLIDATION of the industrial PRODUCTION and manufacturing QUALITY for ALL the main MPGD families.

- Major improvement of the MPGD simulation software framework for small structures allowing first applications;
  - IMPROVEMENTS on METHODS and TECHNIQUES ; APPLICATION for MPGD optimization

- Development of common, scalable readout electronics (SRS) (many developers and > 50 user groups); Production (PRISMA company and availability through CERN store); Industrialization (re-design of SRS in ATCA in EISYS);
  - SUPPORT and continuous DEVELOPMENT
  - NEW BASELINE FE ASICS (from experiment development) and STRUCTURES .
  - Development of EASILY accessible MPGD laboratory INSTRUMENTATION.

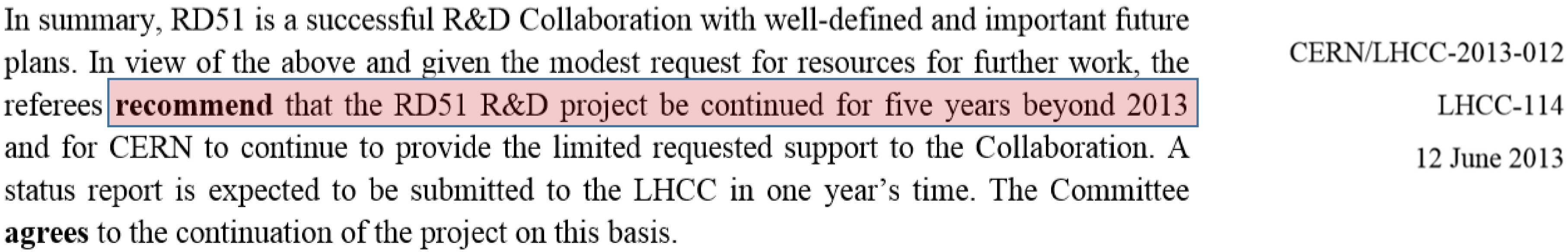
- Infrastructure for common RD51 test beam and lab facilities (>20 user groups)
  - Largely ENLARGED infrastructure for the RD51 LAB. REFINEMENT of the TEST BEAM infrastructure.

RD51: Road map for MPGD Technologies development

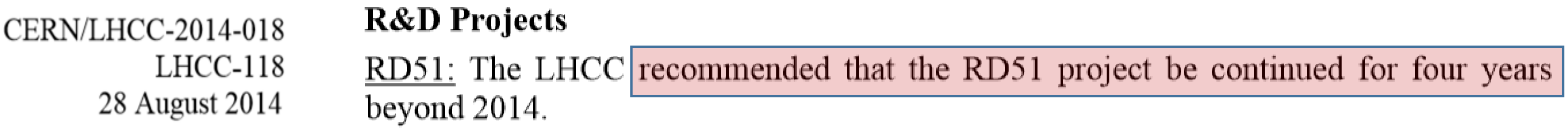


Existing detection concepts have been improved and new ones introduced thanks to new and affordable techniques

After the first 5 years !!!


In summary, RD51 is a successful R&D Collaboration with well-defined and important future plans. In view of the above and given the modest request for resources for further work, the referees **recommend** that the RD51 R&D project be continued for five years beyond 2013 and for CERN to continue to provide the limited requested support to the Collaboration. A status report is expected to be submitted to the LHCC in one year's time. The Committee **agrees** to the continuation of the project on this basis.

CERN/LHCC-2013-012
LHCC-114
12 June 2013

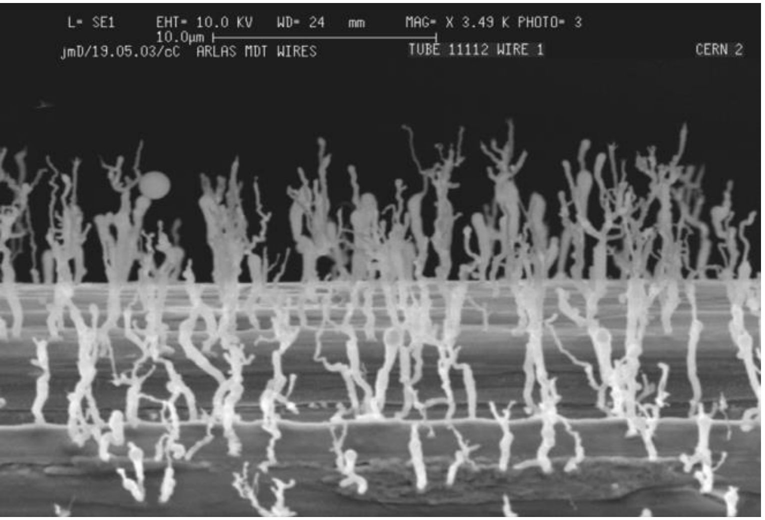

CERN/LHCC-2014-018
LHCC-118
28 August 2014

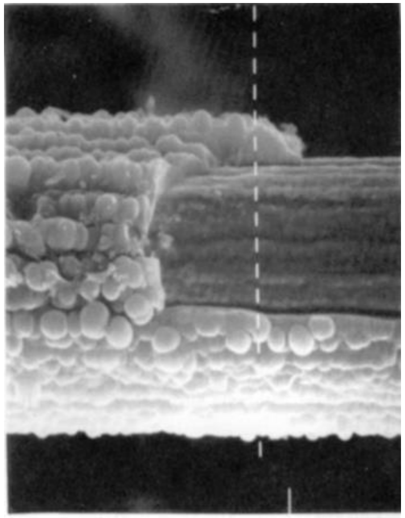
R&D Projects

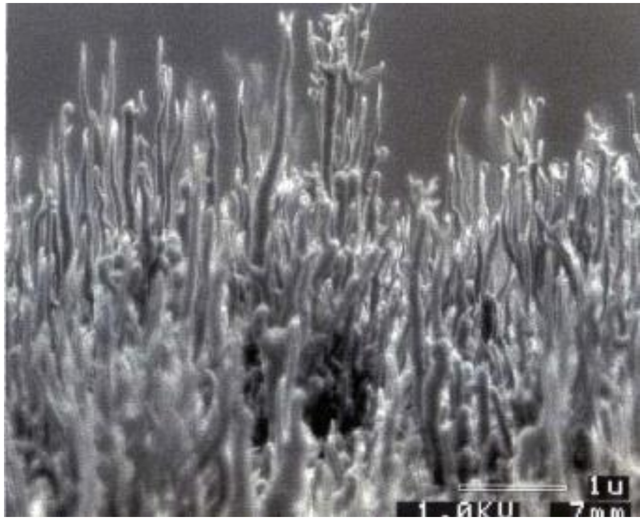
RD51: The LHCC recommended that the RD51 project be continued for four years beyond 2014.

Gaseous detectors: Multi Wire Proportional Chamber

- ⇨ **Limited multi-track separation:** mechanical instabilities due to electrostatic repulsion - critical length of about 25 cm for 10µm wires and 1mm spacing
- ⇨ **Fast gain drop at high fluxes:** field-distorting space charge accumulation due to the long time taken by the ions produced in the avalanches to clear the region of multiplication
- ⇨ **Aging:** permanent damage of the structures after long-term exposure to radiation
  - ❖ due to the formation of solid deposits on electrodes.







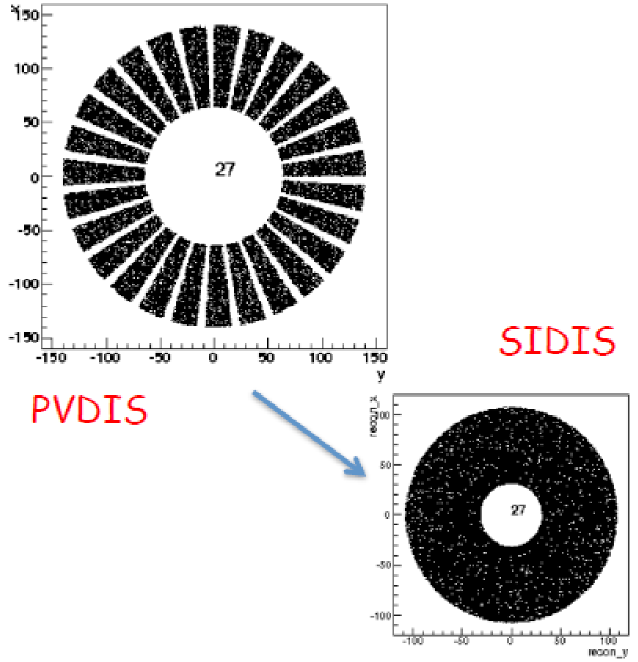
Anode Aging: drop of the gain, discharges

Cathode Aging: Malter effects

SIDIS GEM full configuration

- Six locations instrumented with GEM:
- PVDIS GEM modules can be re-arranged to make all chamber layers for SIDIS. – move the PVDIS modules closer to the axis so that they are overlapping with each other

Plane	Z (cm)	R_I (cm)	R_O (cm)	Active area (m^2)	# of channels
1	-175	36	87	2.0	24 k
2	-150	21	98	2.9	30 k
3	-119	25	112	3.7	33 k
4	-68	32	135	5.4	28 k
5	5	42	100	2.6	20 k
6	92	55	123	3.8	26 k
total:				~20.4	~ 161 k

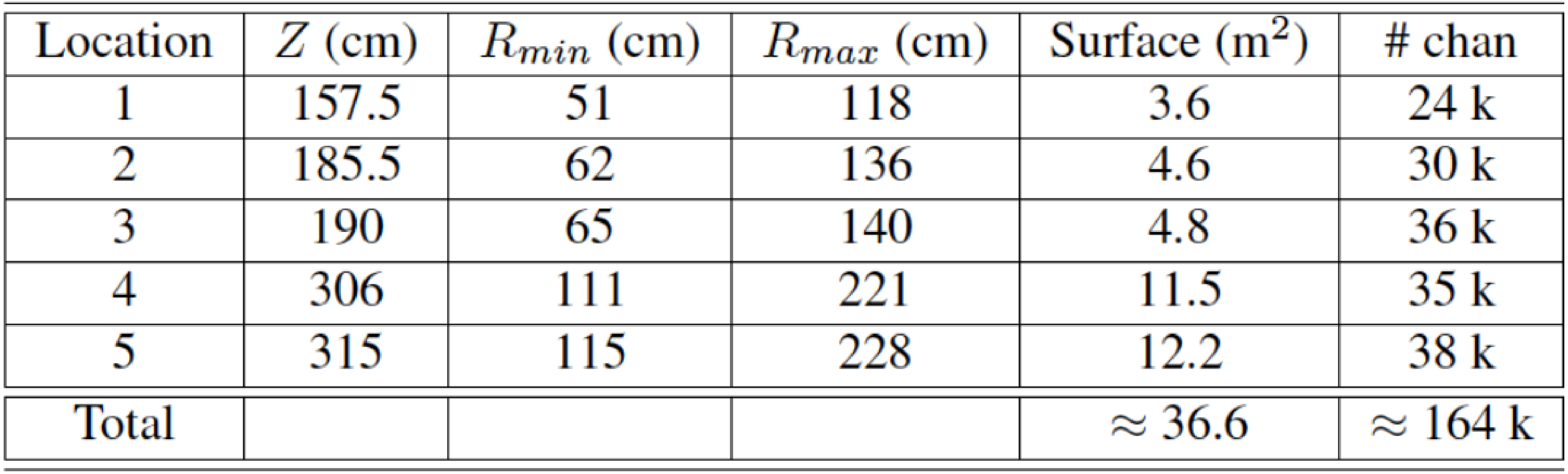


- More than enough electronic channels from PVDIS setup.
- The two configurations will work well with no need for new GEM or electronics fabrication.

MPGDs in Hall A @ JLab: SoLID GEM

PVDIS GEM full configuration

- Instrument five locations with GEMs:
- 30 GEM modules at each location: each module with a 12-degree angular width.



Location	Z (cm)	R_{min} (cm)	R_{max} (cm)	Surface (m^2)	# chan
1	157.5	51	118	3.6	24 k
2	185.5	62	136	4.6	30 k
3	190	65	140	4.8	36 k
4	306	111	221	11.5	35 k
5	315	115	228	12.2	38 k
Total				$\approx$ 36.6	$\approx$ 164 k

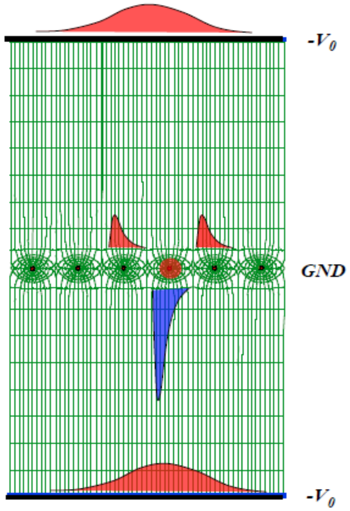
- The high occupancy at location 1 will require splitting each readout strip into two channels: this will add another 12 k channels
- Total number of channels needed: ~ 176 k
- With ~ 15% spares (to account for losses during production etc.) need to plan for

200 k channels

Gaseous detectors: Multi Wire Proportional Chamber

MWPCs:

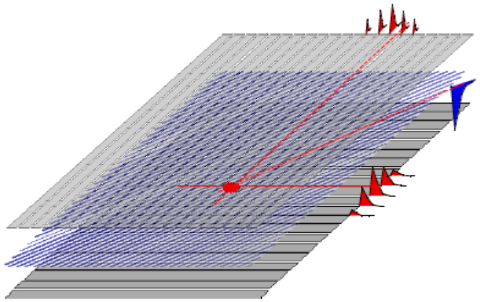
⇨ Fast Position Sensitive Devices, High rate capability, Sub mm position accuracy



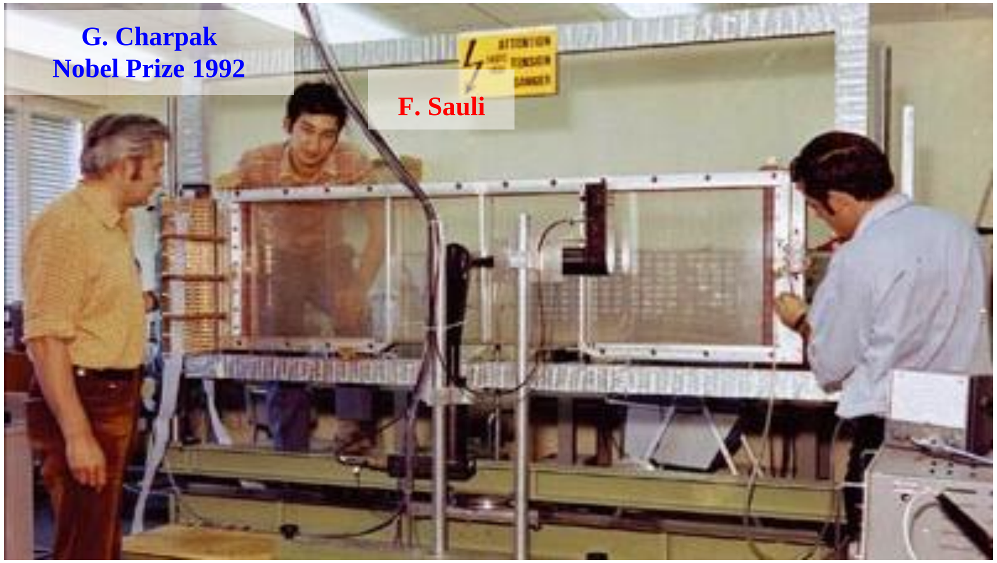
G. Charpak et al,
Nucl. Instr. and Meth. 62(1968)235

TWO-DIMENSIONAL COORDINATE READOUT
Center of gravity of induced signals on cathodes

$$X = \sum \frac{X_i A_i(X)}{A(X)} \qquad Y = \sum \frac{Y_i A_i(Y)}{A(Y)}$$



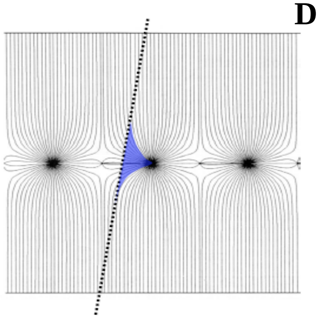
G. Charpak and F. Sauli,
Nucl. Instr. and Methods 113(1973)381



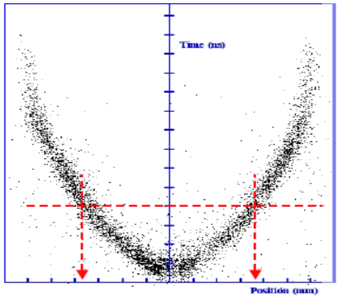
G. Charpak
Nobel Prize 1992

F. Sauli

Drift chambers



A. H. Walenta, J. Heintze and B. Scürlein,
Nucl. Instr. and Meth. 92(1971)373



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