Micropattern Readout Development for Gas Detectors

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Why GEM?

An intensive R&D of many groups demonstrated:

Detectors on a basis of GEM technology can be

- reliable (COMPASS, two years experience)
- high gas amplification (multiple GEMs: up to $10^6$)
- fast (< 20 ns FWHM, rate capability up to $10^5$ Hz/mm²)
- low mass (50 µm Kapton+10 µm Cu; small thickness read-out plane; small size, low Z frame material)
- 1d-, 2d- good space resolution (~50 µm)
- not complicated and inexpensive in a construction

tracking devices that are working with different gases, inside of a strong magnetic field and for a very broad application variants.

Detector response simulation is in a “reasonable” shape.
GEM Detector

Low mass; fast; not “high” precision in construction and in-expensive; any shape and pad size; double, triple or more foils setup; checked and tested.
Space and time resolution (an example, not the record)

Space resolution:
\[ \sigma = 57 \, \mu m \]

Time resolution:
\[ \sigma = 12.4 \, ns \]

Read-out plane: pads, strips, 2D-strips with stereo angle, direct Si, …- choose pitch, technology and shape.
The GEM technology in TPC (motivation)

- Fast and “narrow” signal: electron collection, no ion tail
- Much easy “mechanical” construction, no wire tension – no “strong” frame; smaller thickness both field cage(s) and end-cup
- Flexible foil and pad geometry
- Ion feedback suppression
- Low distortions due to ExB (in amplification region)

The GEM technology in Pad (Strip) Detector (motivation)

- high precision
- low mass
- fast
- not “complicated” in a construction and in-expensive
- any shape and pad size
- double, triple or more foils setup
- can be used in a combination with another detectors
R&D activities: e+e- LC, LHCb, JLab, LEGS, PHENIX, STAR, ...

- GEM pad structure (TPC and Pad Detector)
- “working” gas including UV transparency and scintillations properties
- space and time resolution study
- GEM mass production and dedicated Test Laboratory
- photodetectors (Gas PMT)
- FEE, DAQ, ....
- prototypes
- simulation / reconstruction software
Micro-wire, MIPA and MicroMeGas Detectors.

MIP: MICRO PIN ARRAY DETECTOR (SILICON TECHNOLOGY)

Micromegas

- NIM A376 (1996) 29
- A $1.5 \times 1.5 \text{cm}^2$ detector has been tested at PSI in a low energy hadron beam and at CERN PS with 10 GeV $\pi^+$:
  - 100 $\mu$m amplification gap, 317 $\mu$m strip pitch

- At PSI a very high discharge probability per particle was observed:
  - With $\Delta E - \text{CO}_2$ (62-450) at a gain of 6000 $P = 1.1 \times 10^{-6}$
  - With 50 KHz/mm² proton beam the sparking rate was as high as 3 KHz and the current was 2 mA
- No damage to the chamber has been observed
STAR Detector R&D

Installed R&D Laboratory at BNL (with very low funding so far) as a joint activity with BNL Instrumentation Division, PHENIX, LEGS.

Accomplishments:

- “working” gas including UV transparency and scintillations properties
- GEM pad structure (TPC and Pad Detector)
- GEM mass production and dedicated Test Laboratory (at Yale?)
- UV photoconverters
- FEE, DAQ, …. (first prototype)
- Full scale prototypes (E-field simulation, construction approaches)
- Simulation / reconstruction software

but we need “STAR R&D team”
Test Drift Cell

Drift Stack
presently 29 cm drift

Used to study
- Drift velocities
- Diffusion parameters
- Energy loss (dE/dx)
- Study impurities
- Readout structures
- Field cage design

Lab 2-86 in Physics

Laser
Upper fixed source

Lenses
Triple GEM

Lenses
Lower movable source
Readout Electronics

$^{55}$Fe source with 10x10 cm$^2$ triple GEM, one pad (0.2x1. cm$^2$) signal

FADC readout (10 ns bins)  Digital scope trace

Currently reading out GEM TPC with 100 MHz FADC
(SIS 3300 8 channel, 12 bit VME module)
Drift Cell Measurements

Ar/CO₂ (80/20)

Possible discrepancy
• Gas mixture uncertainty
  • 300 ppm O₂
  • 10-15 ppm H₂O

Energy Resolution
(Top ⁵⁵Fe source)

22% FWHM/mean

Drift Velocities (laser)

Ar/CF₄ (95/5)

28% FWHM/mean

* Data
  o Garfield

* Data
  o Garfield

Drift Velocities (laser)
GEM Detector with 200 µm strip readout

Improved multi-track resolution

Fast signals (no ion tail) 
$\Delta T \sim 20\ ns$:

Narrow pad response function ($\Delta s \sim 1\ mm$):

Intrinsic multi-track resolution $\Delta V \sim 1\ mm^3$ 
(Standard MWPC TPC $\sim 1\ cm^3$)
Charge Distribution from Drift Cell
top source (29 cm drift), 2 mm pad readout

Ar/CO₂ (80/20)

Ar/CF₄ (95/5)

Measured

Simulation

pad number-4

$\text{s}=1.2 \text{ mm}$

$\text{s}=1.7 \text{ mm}$

$\text{s}=1.1 \text{ mm}$

$\text{s}=1.4 \text{ mm}$
New GEM Foils from 3M

3M Microinterconnect Systems Division, Austin, TX
In collaboration with Univ. Chicago (J.Collar)
hep-ex / 0304013 (April 2003)

Roll-to-roll process
Limited to 12” width

Mass GEM foils production can be started in Russia and Japan this year
Testing Small 3M Foils

80 mm (55 mm) holes spaced in a hexagonal pattern with 140 mm pitch
Visually looks to be excellent quality
3 stage GEM with three 1” dia. 3M foils

Will compare with CERN foils in Ar/CO$_2$ & CF$_4$
Absolute Quantum Efficiency of CsI photocathodes

Comparison of our CsI photocathodes with a calibrated CsI PMT

- Smpl. 1: Al, 0.54 microns
- Smpl. 2: Cu+Ni+Au, 0.66 microns

Good quality CsI photocathodes are now being made at Stony Brook

Stack with Au coated GEM foil for depositing CsI photocathode

VUV Spectrometer
Future TPC readout electronics development
(BNL Instrumentation Division, Nevis, Stony Brook)

Try and utilize existing or soon to be available components
Perhaps can use FADC to provide time information

65 MHz FADC available soon
32 ch preamp/shaper for APD readout
0.18 mm CMOS, 125 mW per chip
Final ASIC 4.3 x 1.6 mm²
STAR Detector R&D Plan for Next 2-3 Years

- Build and install in STAR GEM Pad Detector(s) (FEE, DAQ, …?)

- Build and test miniTPC & Cherenkov Detector prototypes

- Locate and build a GEM foils testing and calibration facility (at Yale, MIT ?) (for many today and future applications and experiments).

- Complete design of a readout electronics “first prototype” (IC or …? )

- Start engineering design of TPC/Cherenkov Detector system

- Continue software activity
  - E-field quality, field cage variants, distortions, ExB, “space charge”, mechanical stability, …
  - Detector response simulation.
  - Experiment performance study for different Physics goals.

But still in STAR:
  - No R&D team
  - No $$$
  - No needed support

Many new approaches, hard work and a lot of enthusiasm has been demonstrated. Our 3 years old, “fresh” ideas became “good” ones; ~6 R&D teams are very active
Several TPC prototypes, large and small, are now in operation. Shown here is the large one in DESY/Hamburg which uses cosmic rays to study the tracking characteristics using GEM gas-amplification. Obviously these studies are with no magnetic field. The size of the chamber is suitable for studies of gas properties and of the impact of readout geometry on the coordinate resolution.
Double GEM TPC Cosmic Ray Tests
Carleton/Victoria/Montreal

- Aleph TPC preamps + Montreal 200 MHz FADCs
- 15 cm drift (no B field)
- **Pads can share track charge due to transverse diffusion**
  - Ar CO$_2$(90:10), small $\sigma_T \sim 200 \mu m / \sqrt{cm}$
  - P10 Ar CH$_4$(90:10), large $\sigma_T \sim 500 \mu m / \sqrt{cm}$
- Compute pad centroids, measure resolution for different width pads

The photograph shows the Carleton test chamber using GEMs. Again there is no magnetic field, and the pad layout is with 3x multiplexed readout (thus the mirrored hits in the right diagram). Drift distances up to 15cm, two different gases (Argon with CO2 or CH4) and resolution with different pad widths (2mm and 3mm) have been studied; the pads were rectangular and charge sharing took place via transverse diffusion in the induction gap (between GEM and anode). The track was defined by outer rows (3 on each side) and the resolution measured on the middle rows.
Resolution vs Drift Distance for Different Pad Widths

$|\varphi| < 0.1$

Carleton/Victoria/Montreal

Single pad row resolution measurements from the Carleton TPC. Tracks are formed from the outer 6 rows, and residuals calculated for each of the two inner rows with 2mm x 6mm (triangles) and 3mm x 5mm (circles) pads. The residuals are fit to Gaussians, and the standard deviations (in microns) is shown here for different drift distances.
Left: The 5T superconducting solenoid at DESY which started operation at the end of last year. First tests (see below, p.11) were made using a small GEM device built at Aachen to allow measurement of all currents in order to derive the charge-transfer characteristics. Similar measurements had previously been carried out in a 2T magnet at Jülich.

Right: The 2T superconducting solenoid magnet in operation in Saclay has a 53 cm bore diameter and a length of 150 cm. It has been used for testing two Micromegas TPCs and a wire TPC built by Saclay/Orsay using current measurements. It is now being equipped with a 1000-channel cosmic ray Micromegas prototype with a 50 cm drift length.
Example events at ~25 cm drift
Gas: P10

0 Tesla

0.45 Tesla

0.9 Tesla

$\sigma = 2.3$ mm

$\sigma = 1.2$ mm

$\sigma = 0.8$ mm
TPC cosmic tests at Karlsruhe

Cosmic ray setup using STAR electronics
Measured resolution 124 µm, S/N = 18:1

The Karlsruhe test chamber with GEMs (left) has recorded cosmics and was also exposed to a test beam in CERN. The figure on the right shows a measured track. The readout took place using the STAR electronics test-stand supplied by LBNL. The tests were with no magnetic field, but the chamber can fit into the 5T magnet at DESY.
Here are the results mentioned above (p.10) which were obtained with the Aachen test chamber in the DESY magnet, and which confirm and extend previous measurements carried out at Julich. The various currents arise from an Fe55 source. The anode current (electrons arriving at pads) rises significantly with B-field. In order to understand this, the triple-GEM structure was operated with symmetric settings (GEM voltages at 330V and transfer fields at 1kV/cm) so that all GEMs have equal collection efficiency C, gain G and extraction efficiency X, and the anode current was the primary current times \(C^3G^3X^3\). The collection times gain drops slightly while the extraction improves, meaning only few primary electrons are lost during collection at 5T while the net gain of the overall structure increases at higher B-fields.
Left: the ion-feedback improves at high magnetic field in GEMs, as seen from the Aachen/DESY measurements described on pp.10-11.

Right: Positive ion feedback fraction as a function of magnetic field, as measured in the 15cm Orsay/Saclay Micromegas TPC. No dependence on the magnetic field is observed, consistent with expectations, and it is about 3 times the optimal feedback due to the use of a relatively coarse micromesh (500 lines per inch). A finer mesh (1000 lpi) should allow reaching the optimal feedback with this gas (Ar10%CH4).
At NIKHEF a new idea is being tried out, namely to read out a TPC using a Si detector with pixels matching the GEM-hole pitch. Left: the MediPix2 chip has 256 x 256 pixels of 55 x 55 µm², low noise and a minimum threshold of about 1000 electrons. Right: schematic view of the one liter test TPC with a triple-GEM arrangement and an insert in the base plate for the MediPix2 chip.
Three test chambers have been built in Aachen (see also below) and detailed simulations on GEM properties are also being carried out. On the left are the simulated electron-drift trajectories in a GEM using the programs MAXWELL and GARFIELD, and on the right is the calculated extraction efficiency compared with measurements. The black curve is a parameterization of results from simulation with MAXWELL only, which is adequate for gases with small diffusion. The data points labeled “MC simulation” are due to the combination of MAXWELL+GARFIELD so that diffusion is included. That simulation and results agree well will be important for the final optimization of a GEM TPC readout.
Simulation (NS) – Data ("Canada")
small TPC, double GEM, 5 pad rows, P10, cosmic

Pad size 2.\times6. \text{mm}^2

Pad size 3.\times5. \text{mm}^2

Experimental data

"gauss fit"

"nonlinearity correction"
GEMs + CsI as UV Detector

- Windowless Cherenkov detector
- Radiator and detector gas: CH4, CF4
  Large bandwidth:
  in a case of CF4; $N_0 \approx 960$ and $N_{pe} \approx 40$!!
- Reflective CsI photocathode
  No photon feedback
- Proximity focus $\rightarrow$ detect “blob” or “road”
  And can or can’t be “sensitive” to MIP
- Detector element: multi-GEM
  stable operation at high gain

Novel but very challenging. MWPC with Pad readout is the “standard” solution
Single Photoelectron Detection Efficiency

measure detector response vs $E_D$ at fixed gain
(Weizmann Inst of Science)

Very efficient detection of photoelectrons even at negative drift fields!!
Cosmic ray tests: Experimental Set-up

Cosmic trigger

- S1.S2.S4

C: CO₂ radiator

- $p_{th} \sim 3.8$ GeV
- 1.30 m long
- rate $\sim 1$/min

CF₄ Radiator

- 50 cm long
- directly coupled to detector

Detector Box

- triple GEM + CsI
- test with Fe⁵⁵, UV lamp, $\alpha$

Detector Box

CF₄ Radiator

C: CO₂ radiator

Cosmic trigger

S1. S2. S4

C: CO₂ radiator

CF₄ Radiator

Detector Box

Cosmic trigger

S1. S2. S4

C: CO₂ radiator

CF₄ Radiator

Detector Box

Cosmic trigger

S1. S2. S4

C: CO₂ radiator

CF₄ Radiator

Detector Box

Cosmic trigger

S1. S2. S4

C: CO₂ radiator

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Detector Box

Cosmic trigger

S1. S2. S4

C: CO₂ radiator

CF₄ Radiator

Detector Box

Cosmic trigger

S1. S2. S4

C: CO₂ radiator

CF₄ Radiator

Detector Box

Cosmic trigger

S1. S2. S4

C: CO₂ radiator

CF₄ Radiator

Detector Box

Cosmic trigger

S1. S2. S4

C: CO₂ radiator

CF₄ Radiator

Detector Box
Set-up

Overall Set-up

Detector Box

Detector Box

50 cm long CF₄ Radiator

D₂ UV Lamp

Mesh ................................. 1.5mm

Am²⁴¹ or Fe⁵⁵

1.5mm

GEM1 ................................. 1.5mm

1.5mm

GEM2 ................................. 1.5mm

1.5mm

GEM3 ................................. 2mm

PCB ................................ 2mm

(9 3x 3 cm² pads)

Powering scheme

Independent powering of the mesh

R = 10MΩ

Resistive chain

Powering of triple GEM
Possible detector combinations

GEM +

- MicroMegas
- microstrip
- 4 more GEMs + photoconverter → “gas phototube”
- Si pixel

( photon polarization, neutron detector, liquid drift detector, ....)
GEM development and R&D Laboratory

GEM foils mass production; “crucial step”: foils $\rightarrow$ Detector

- CERN, COMPASS experience
- US company was found (we hope) to produce high quality and needed size GEM foils. Foil samples are under study now
- Locate and build a GEM foil testing & calibration facility (at Yale, MIT ?)

Very promising and interesting future

- STAR tracking and PID
  - barrel
  - “EEMC direction”
  - “very forward” coverage
  - miniTPC
- eRHIC tracking and PID
- ee LC
- Medical Imaging
- Student education
- and much more
Final Comment

Please, take a decision, timing is crucial

“The steed of the Time is tirelessly racing on a clock-face of the Eternity”
Peter Estenhazy.