Particle Tracking and Hadron Therapy Beam Monitoring with GEMPix – a Highly Pixelated Triple GEM Detector

Stuart P. George
Particle Tracking with Gempix - a Timepix Based Gas Detector

S. P. George\textsuperscript{1,2}, F. Murtas\textsuperscript{1}, J. Alozy\textsuperscript{1}, A. Curioni\textsuperscript{1}, A. B. Rozenfeld\textsuperscript{2}, M. Silari\textsuperscript{1}

\textsuperscript{1} CERN, Geneva, Switzerland
\textsuperscript{2} University of Wollongong Centre for Medical Radiation Physics, Wollongong, NSW, Australia

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How does the Gempix Work?

- Initial electrons created by an interaction are transported by electric fields to the GEM foils.

- Each GEM foil creates up to 40 output electrons for each electron in, three GEM foils give gains up to $10^5$ (depending on the gas).

- These electrons are collected by the Timepix, ~1000 electrons is enough to trigger a pixel (high gain operation).
GEM Detectors

- A GEM consists of a large kapton sheet with both sides metallized.
- A potential is placed across both sides and tiny holes etched in the detector.
- Electrical fields can reach ~100 kV/cm inside the holes, allowing for a localised electron avalanche.

Image CERN GDD Group (2001)
A GEM consists of a large kapton sheet with both sides metallized.

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7 Independent electric fields - GEM 1, 2, 3 control the gas gain $E_{\text{Drift}}$, $E_{\text{Transport}}$, and $E_{\text{Induction}}$ transport electrons through the detector.
The Gempix - An Ultra Pixellated Gas Detector

Sensitive area = 3 x 3 x 1.2 cm$^3$

(1) Gas Supply
(2) High Voltage
(3) Entrance Window
(4) GEM Foils
(5) FITPix Readout
The Timepix - a quick intro

- The timepix asic consists of 256 x 256 CMOS pixels each measuring 55 x 55 um.

- Each pixel can either measure charge deposited or do single particle counting.

- The detection threshold is about 1000 electrons, noise width about 100 electrons

- We use a quad configuration of 512x512 pixels for a total of 262144
Medipix (pulse counting)

TOA (Time of arrival)

TOT (Charge surrogate measurement as a Wilkinson ADC)

TOA/TOT achieved with an on chip clock synchronised to all pixels (up to 100 Mhz, but 50 stable)
Fe55 Photoelectron (5.9 keV)
Argon escape/fluorescence ka (3.0 keV)

Cluster due to light

Gas Mix = Ar:CO$_2$CF$_4$ (45:15:40), Gain = 1350V = 2.10$^4$
Gain Scan with Fe55

Number of Clusters as a function of gain

Cluster TOT as a function of gain

Working point at 1230 V
Alpha Particles (~6 MeV Am241)

Number of Clusters as a function of gain

Cluster TOT as a function of gain

Working point at Gain ~950V, compare with 1230V for Fe55
870 V
Length ~ 1 mm, vol ~70 px

930 V
Length ~ 1.7 mm, vol ~200 px

990 V
Length ~ 1.8 mm, vol ~350 px

1050 V
Length ~ 1.9 mm, vol ~600 px
TOT/keV vs Gain Voltage, IKrum = 1, Clock = 9.6 MHz

\[ y = 3.0408 \times 10^{-11} \times e^{0.031158x} \quad R = 0.99424 \]
Spectra - $^{55}$Fe (5.9 keV)

18.3% Energy Resolution on the corrected Fe Peak
Typical Frame - $^{55}\text{Fe}$ (5.9 keV)

Response of 8x8 pixel regions

Mapped average response from gaussian fit
Maximum Count Rate (Xray tube, 40 kVp)

• Single interaction defined with clusterable data

• Maximum count rate \( \sim 10^7 \text{/s} \) (\( 10^6 \text{/cm}^2 \text{/s} \))

• Some room for optimisation by changing asic settings (factor 2 variation)

• Possibly an effect of the relatively high gain needed to readout the Timepix?
Particle tracking (CERN SPS MIP's) - TOA Mode

Total dT ~ 400 nS

The main limitation of this mode is the maximum frame length, = 248 uS. This leads to a very large dead time
Effect of Chamber Gain

Everything

Candidate Tracks (>100px)

Photo-sensitivity (e- off Al)

![Graph showing the effect of chamber gain on the number of objects and candidate tracks with respect to total gain.](image-url)
Measurement of Drift Velocity (vary drift field)

Track top/bottom delta times (morphological operator for time walk correction)

Drift Velocity (mean from gaussian fit of curves on left)

![Graph showing track top/bottom delta times and drift velocity](image)

![Graph showing drift velocity vs. drift field](image)
Track Reconstruction

3D Least Squares Fit of 3 GeV MIP
Track Incident at 30 Degrees

Illustrative (1/16 pixels drawn)
Fig 8

(a) Theta plot showing frequency distribution for different beam angles. The plot includes data for 10 Deg, 20 Deg, 30 Deg, and 40 Deg.

(b) Phi plot showing frequency distribution for different beam angles. The plot includes data for 10 Deg, 20 Deg, 30 Deg, and 40 Deg.

(c) Angular Resolution plot showing the relationship between beam angle and angular resolution. The plot compares Theta and Phi resolutions for different beam angles.
Spatial Resolution

\[ R = 170 \, \mu m \]
\[ R_{px} = 17 \, \mu m \] (mostly because the time resolution is poorer than the spatial resolution)
Mixed Mode Operation

Note, TOA pixels are doubled in lateral size for visual effect
**Gempix Energy Deposition Spectrum**

PAI -> Geant4 PAI model, range cut = 0.1 mm, mono energetic 3 GeV 2/3 proton, 1/3 pi+ pencil beam on 24 mm ArCO$_2$CF$_4$

Gaussian + PAI -> Smearing following: $\sigma = A\sqrt{\Delta E(\text{keV})}$

Angular Reconstruction - Mixed vs TOA

Fig 11
Angular Reconstruction - Mixed vs TOA
Avalanche Statistics

Fit with $y = a + \sqrt{bx}$

B factors not constant - threshold effects?

Plot of intercept parameter from left (charge cloud width ‘just’ from GEM structure)
An Application - Microdosimetry

- The study of radiation interactions at the scale of cellular structure

- The number of atoms in a 5 mm path in gas is about the same as in a cellular nucleus

- Typical instrumentation is a single low pressure gas volume or silicon volume

- Gas pixel detectors offer the ability to examine each track individually
Towards Microdosimetry

Target

Kapton Window

Triple GEM

Gas In/Out
Fig 15
Hadron Therapy

- Hadron therapy uses beams of Protons and Carbon ions to treat cancer
- Exploits the energy deposition properties of charged hadrons (Bragg peak)
Hadron Therapy

• ~30 centers worldwide (Majority in USA, then Japan)

• ~150 million for one centre (~2k patients/yr)

• Economics arguments often produce numbers such as 1 centre per ~20 million people - though cost benefit is contentious

• **Limited QA tools compared to photon therapy**
Proton radiation therapy is potentially a better way to treat cancer because it has fewer side effects, but the technology is still very expensive. The University of Florida Proton Therapy Institute required eight years and $125 million to build, and it can serve up to 150 patients a day.

**Cyclotron**
Using magnetic fields, the cyclotron can accelerate the hydrogen protons to two-thirds the speed of light.

**Electromagnets**
The magnets focus the proton beams toward the gantry.

**Nozzle**
A 21,000-pound magnet guides the beam to the patient through a nozzle.

**Gantry**
The gantry can rotate 360° around the patient to position the nozzle.

By adjusting the speed of the protons, a physician can control how deep their penetration will be. The protons then release their energy at the tumor and cause less damage to the surrounding tissue.

Because conventional radiation doesn’t release its energy at a specified depth, it can cause more damage to the tissue surrounding the tumor.
Beam Monitoring Measurements for Hadron Therapy

- Proton beams at CNAO (National Centre of Oncological Hadrontherapy) in Pavia, Italy
- Started treatment in 2011
- Proton fluences ~$10^{10}$/cm$^2$s
Proton Beam at Different Gains

160 MeV proton beam, flux ~ $10^{10}$/cm$^2$s

Gain 930 - 0.001s frame

Gain 990 - 0.001s frame
Proton Beam at Different Gains

The gain can be used to set a minimum ‘threshold’ on the per particle dE/dx - measurements of unusual events.
Gempix as a Beam Monitor

480 MeV/A carbon ions, 0.01s frame, **ASIC in particle counting (medipix) mode**, IKrum = 5
Overall beam shape

Counts
Halo, down to single particle resolution
Spot Scan ...
Detector Linearity

90s measurement, 1s spill, spill every 5 seconds

Counts are the integral over the total 90s period

Number of ions is the counts/average carbon cluster size (~130 pixels)

(Dead time is significant however ~1/10)
Time Profile of Particle Spill

Counts

$\times 10^6$

Time (s)

0 15 20 25 30 35

Counts
Energy Deposition Measurements for Hadron Therapy

- 480 MeV/A Carbon Ion Beam at CNAO
- 23 different depths throughout water phantom
- Each position given spot $10^7$ carbon ion treatment
Stepper Motor
Gempix
Phantom
Thin Window
Results at CNAO

Simulation/figure by A. Tamborini
Systematic underdose in fragment tail needs to be explained
Beam spot lateral dimensions as a function of depth in water

Simulation/figure by A. Tamborini
3D Beam Reconstruction

- **Bragg Peak**
- **Fragment Tail**
- **Beam Entry**
Future Thoughts

• A GEMPix based on the new Timepix3 ASIC will solve many of the dead time issues in tracking.

• GEMPix as a microdosimeter is mainly advantageous over normal TEPC’s because it measures track by track. Possibility to operate at low pressure as a nano-dosimeter.

• Work is underway to perform the CNAO measurements much faster using better integration with the CNAO beam delivery system. In this application it may be useful for realistic QA.
Thanks for your attention