The new CGEM Inner Tracker and the custom TIGER ASIC for the BESIII Experiment

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Torino University and INFN
on behalf of the CGEM-IT Group
Outline

- BESIII Experiment
- The new CGEM Inner Tracker
- Study of Performance at Beam Test
  - Planar and Cylindrical prototypes
- The custom ASIC: TIGER
- Conclusions and Outlook

BESIII Talks in Parallel Sessions
- July 7 - Charm Meson Physics at BESIII by Jiangchuan Chen
- July 8 – Light Hadron Spectroscopy at BESIII by Francesca De Mori
Physics goals cover a large and diverse range
Charmonium, Open Charm and Light Hadron Spectroscopy, $\tau$-physics and more

$$\sqrt{s} = 2 - 4.6 \text{ GeV}$$
Aging of the MDC Inner Tracker

MDC (Main Drift Chamber)
43 layers into Two Trackers sharing the same He-based gas mixture
- Inner Tracker
  - 8 stereo-layers
- Outer Tracker
  - 12 axial layers
  - 16 stereo layers
  - 7 axial layers

Issues
- Significant ageing in the Inner Tracker
- The increase of Luminosity is speeding up the ageing
- Working at lower HV to keep current under control
- Lower Efficiency
- Gain loss/year ~ 4%

Performance
- Spatial resolution $\sigma_r = 130\mu m$
- Momentum resolution 0.5\% @1GeV
- $dE/dx$ resolution 6\%

How to run until 2022 and beyond?
A replacement is needed
CGEM: a new Inner Tracker for future data taking

Replace the 8 layers of MDC with 3 layers of cylindrical triple GEM

Requirements

• Spatial resolution \( \sigma_r, \phi \approx 130 \mu m, \sigma_z \approx 1 mm \)
• Momentum resolution \( \approx 0.5 \% @ 1 \text{ GeV/c} \)
• Rate capability \( 10^4 \text{ Hz/cm}^2 \)
• Efficiency \( \approx 98\% \)
• Material budget \( \leq 1.5 \% X_0 \) all layers
• Solid angle coverage \( \approx 93\% \)
• Magnetic field \( 1 T \)
• Inner radius 78 mm Outer radius 179 mm

• Each layer is made by a triple GEM 5/2/2/2 moulded upon a cylindrical shape
• XV segmented anode
• Readout strips (pitch, X, V) 650/570/130 \( \mu m \)

arXiv:1706.02428

Beneficiaries and Partner Organisation
INFN (FE, LNF, TO)
Mainz U - Uppsala U - IHEP

HEP2017 - Simonetta Marcello - July 5-12, 2017
State of the Art and Innovation

Previous Experiment

- First Cylindrical GEM detector (4 layers) designed and implemented by KLOE-2 at DAΦNE
- Operated at 0.5 T with a spatial resolution of 350 µm
- Digital readout (XV strips with stereo angle 25°-30°)

Innovations @BESIII

- Cathode and Anode frame made of Rohacell instead of Honeycomb
- New anode design with a jagged layout to reduce of 30% the inter-strip capacitance
- Analogue readout to achieve the required spatial resolution with a limited number of channels (~10 000)
  → TIGER, a dedicated custom ASIC to provide Charge and Time measurements by TDC, ADC and ToT
  → Both Charge and Time information will be used to reconstruct the position with B = 1T
Measurements of performance

Beam Test
- Planar GEM December 2014 @ CERN
- Planar GEM June 2015 @ CERN
- Planar GEM May/June 2016 @ CERN
- Cylindrical GEM October 2016 @ CERN
- Cylindrical GEM July 2017 @ CERN

Cosmic rays
- Cylindrical GEM ongoing

@ CERN
- H4 beam line at SPS, North area
- GOLIATH dipole
- B field 1.5 T both polarity

Beam
- Muons/pions
- Momentum 150 GeV/c
- Intensity $10^4$-$10^6$ events/spill

Planar triple GEM prototype

Cylindrical triple GEM
Beam test with Planar triple GEM

- Triple GEM 10x10 cm²
- X view + Y view
- Strip pitch 650 µm
- Gas mixture
  - Ar/CO₂ (70/30)
  - Ar/iC₄H₁₀ (90/10)
- Readout by APV25 ASIC

- Performance measured with different geometries, gas mixtures and E fields
- Efficiency plateau on the two views reaches ~97% at a gain of ~6000

Efficiency ~97%
The Charge Centroid method

A weighted average position is measured from the fired strips and its performance is better than the digital readout, which is limited by the strip pitch.

Orthogonal tracks $\vartheta = 0^\circ$ and $B = 0$
- Charge distribution $\rightarrow$ Gaussian
- Best performance $\rightarrow$ Res. $< 100 \, \mu m$
  $\rightarrow$ Gain $> 6000$
  $\rightarrow$ No. of fired strip $> 2$

Inclined tracks and $B = 0$
$\rightarrow$ Inclined tracks and/or magnetic field increase the Cluster Size
$\rightarrow$ A different method to reconstruct the position is needed

Orthogonal track $\vartheta = 0^\circ$ and $B \neq 0$
- Cluster size increases
  $\rightarrow$ Charge distribution no more Gaussian
- Charge Centroid method fails
Combining Charge Centroid & $\mu$TPC methods

- Inclined tracks and/or magnetic field → Increase cluster size → The $\mu$TPC method can be used
- The drift gap is seen as a micro Time Projection Camber
- The spatial resolution can be improved using the Time information on each strip and the drift velocity

- $\mu$TPC takes into account the Lorentz angle to reconstruct the tracks with $B \neq 0$
- The Lorentz angle using Ar-$iC_4H_{10}$ @ 1.5 kV/cm drift field is $\sim 26^\circ$
  In this region CC is more efficient. In the other regions $\mu$TPC is flat with a resolution $\sim 130$ $\mu$m

A combination of the two methods allows to keep the resolution stable in the full range of incident angles

**Best worldwide Spatial Resolution for Triple GEM in high magnetic field**
Beam test with the Cylindrical triple-GEM

- First beam test @ CERN with prototype of Layer-2
- 3 mm drift gap (new Layer with 5 mm is under assembly)
- Gas mixture Ar/CO₂ (70/30)
- X and V views, only X instrumented

**Goals**

- CGEM at 42° to test the performance along the longitudinal strip @ B = 1 T
- Comparison between cylindrical and planar GEM measurements
- Test the stability of the detector under beam conditions
- Test under high intensity pion beam

**Cylindrical and Planar measurements**

- Orthogonal tracks and B = 0 with Charge Centroid method
- Resolution of CGEM is in agreement with planar GEM → about 110 µm

**Test under extreme conditions**

- HV = 400 V for each GEM foil → gain 10⁵ → Stable
- High intensity beam → some ten of kHz/cm² → No current peaking problem

A second Cylindrical GEM layer is under test @ CERN in these days
Readout Electronics: TIGER ASIC

Our Aim: Spatial Resolution $\leq 130 \, \mu m \Rightarrow$ Analogue Readout is needed

Requirements

- Should provide Charge and Time measurements for Charge Centroid and $\mu$TPC modes and feature a fully-digital output
- Input charge: 1 – 50 fC
- Sensor Capacitance: up to 100 pF
- Rate per Channel: 60 kHz (safety factor of 4 included)
- Time resolution: 4-5 ns
- Power consumption $\sim 10 \, mW/channels$
- Should be radiation tolerant for Single Event Upset

A custom ASIC has been designed and developed TIGER (Torino Integrated GEM Electronics Readout)
TIGER Design

Front End
- Charge Sensitive Amplifier + two shapers (Time and Charge)

Time-based readout
- Single or double threshold readout
- Time stamp on rising/falling edge (sub-50 ps binning quad-buffered TDC)
- Charge measurement with Time-Over-Threshold

Time and amplitude sampling
- Time stamp on rising edge (sub-50 ps binning quad-buffered TDC)
- Sample-and-Hold circuit for peak amplitude sampling
  → Slow shaper output voltage is sampled and digitised with a 10-bit Wilkinson ADC

Back End
- TDC/ADC local controller
- on-chip bias and power management
- on-chip calibration circuitry

First silicon Tape-out
MPW in May 2016
Test on silicon started in Nov 2016

arXiv:1706.02267
TIGER preliminary tests

- T-branch Gain $\approx 10.4 \text{ mV/fC}$ in agreement with simulations
- RMS Noise $\approx 3.5 \text{ mV} @ 100 \text{ pF}$ 50% higher than simulations - RMS Jitter $\approx 3.7 \text{ ns}$ for $Q_{in} = 3 \text{ fC} @ 100 \text{ pF}$
- Charge measurement with S&H: linearity assessed

Electrical characterization
- Time-based readout working properly
- Charge measurement S&H linearity assessed
- Baseline dependence on Temp, due to bias conditions of holder circuit → minor revision needed
- Second Prototype not needed → Engineering Run within July 2017 → to produce 160 ASICs + Spares

Test with CGEM prototype
- First signals acquired with Cosmic rays and $^{90}\text{Sr}$ source – Data analysis ongoing
- Next step: test with conditions close to the final ones (HV system, cables, FEB, ...)

S&H linearity
External Test Pulser

T-branch Gain
Noise vs $C_{in}$
Conclusions and Outlook

- An innovative Cylindrical GEM detector with Charge and Time readout is under construction and test to replace the BESIII Inner tracker which is affected by ageing
- Performance and optimization of a planar GEM prototype have been studied under several conditions (HV, gas mixtures, fields)
- Combining Charge Centroid and µTPC modes, the spatial resolution is stable and results are beyond the state of the art for GEM detectors operated in B field
- A first Cylindrical GEM layer has been tested w/o B field and its performance is close to planar GEM
- A second Cylindrical GEM layer is ready and under test @ CERN in these days
- TIGER: a custom ASIC for analogue readout (featuring Charge and Time measurements) has been developed and it is under test with real CGEM signals with cosmic rays and $^{90}$Sr source
- TIGER engineering run is foreseen with minor revisions and different design flavours within this month
- Three CGEM layers will be tested with TIGER and will be ready for shipping in February 2018
- CGEM detector installation @ IHEP is planned in Summer 2018
GEM Technology

- XV segmented anode
- Readout strips (pitch, X, V) 650/570/130 µm

The GEM foils placed between anode and cathode provide a gain of \( \sim 10^3 - 10^4 \) at lower voltages \( \rightarrow \) lower discharge probability

- The signal depends on the gas mixture, the geometry and the applied fields
- High efficiency needs a gain of \( 10^3 - 10^4 \), while safety standard requires a discharge probability below \( 10^{-5} \)
Physics advantages using CGEM in BESIII

• Better analysis for final states with short life particles
• Better precision on secondary vertex reconstruction
• XV readout improves spatial resolution in z coordinate (2mm → 1mm)
• Triple-GEM technology shows higher resistance to high particle flux
• Triple-GEM technology shows lower aging effects

Vertex resolution of $K^0_s$ and $\Lambda$ particles improves between 2 and 3 times over the drift chamber
The Charge Centroid method

- The avalanche size depends on the gas diffusion, which is affected by E field and gas mixture
- A weighted average position is measured from the fired strips and its performance is better than the digital readout, which is limited by the strip pitch

Results with Orthogonal tracks and B = 0
- The charge distribution on the anode is Gaussian
  → Charge Centroid method

The best performance of CC method is achieved when the number of fired strip > 2
The Charge Centroid method

Inclined tracks and $B = 0$
- The cluster size increases and the charge distribution on the anode is no more Gaussian
  - Charge Centroid method fails
The Charge Centroid method

Inclined tracks and/or magnetic field increase the cluster size

A different method to reconstruct the position is needed
The µTPC method

• Inclined tracks and/or magnetic field → Increase cluster size → The µTPC can be used
• The drift gap is seen as a micro Time Projection Chamber
• The spatial resolution can be improved for inclined tracks and with $B \neq 0$
  using the Time information on each strip and the drift velocity

Knowing the drift velocity from Garfield simulation, a bi-dimensional point is assigned to each fired strip. These points are used to reconstruct the track in the conversion region.
• A linear fit is used to reconstruct the path and to measure the particle position
The µTPC method vs Charge Centroid

- Inclined tracks and/or magnetic field $\rightarrow$ Increase cluster size $\rightarrow$ The µTPC method can be used
- The drift gap is seen as a micro Time Projection Camber
- The spatial resolution can be improved using the Time information on each strip and the drift velocity

Comparing the two methods

A combination of Charge Centroid and µTPC methods is needed
Inclined tracks and $B \neq 0$

Two different effects can be observed:

- **focusing effect**: Lorentz & inclination angles concordant → smaller cluster size
- **de-focusing effect**: Lorentz & inclination angles discordant → bigger cluster size
Readout Electronics

- **ON-DETECTOR ELECTRONICS**
  - ~10 000 CHANNELS
  - TIGER-based Front End Electronics
    - 160 ASICs in 40+40 FEBs
    - 128 channels each
  - Data & Config LVDS
    - ~10 m
  - GEM ROC Readout Modules
    - 10+10 GEM ROCs

- **OFF-DETECTOR ELECTRONICS**
  - Monitoring and standalone DAQ
  - GbE link
  - Data & Config
  - Optical links
  - GEM DC Data Collector Modules
    - 2 DCs

• **ON-DETECTOR electronics**
  Front End boards located on the detector to preserve the S/N ratio

• **OFF-DETECTOR electronics**
  Readout Cards and Data Collector boards as close as possible to the detector