# Particle Identification with the High Granularity TPC Readout ROPPERI

Readout Of a Pad Plane with ElectRonics designed for plxels



Ulrich Einhaus (DESY) Jochen Kaminski (Uni Bonn), Michele Caselle (KIT) 11<sup>th</sup> Terascale Annual Meeting 28.11.2017





HELMHOLTZ





#### Content

- Introduction & Idea
- Hardware
  - Board structure
  - Development status
- Simulation
  - Cluster counting
  - MC chain structure
  - Identification performance



### ILC - ILD - TPC

- Work done within the Helmholtz programme Matter & Techonologies
- Design study in the framwork of International Linear Collider (ILC) – International Large Detector (ILD) – Time Projection Chamber (TPC)
- But: rather generic TPC techology development





### ILC - ILD - TPC







- For a GEM-based TPC readout: Match readout pitch with dimension of primary ionisation clusters
- Allow for:
  - Improved particle identification by dE/dx (cluster counting)
  - Improved double hit/track resolution
- Implementation:
  - Use separate pad plane for high flexibility and large area coverage
  - Use pixel chip for high integration  $\rightarrow$  Timepix



- GEMs, small pads, Timepix chip as readout electronics
- Connections from pads to chip are routed through the board, then bump bonded to the chip
- Timepix: 65,536 pixels, 55 µm pitch



#### **Benefits**

- Compared to the existing GEMs+pads system:
  - Higher granularity  $\rightarrow$  better occupancy, double track resolution, possible cluster counting
  - Square pads, several pads per charge cloud  $\rightarrow$  no tan<sup>2</sup> $\theta$  -effect
  - High integration: O(30) smaller footstep
- Allow for "arbitrary" pad sizes, full anode area coverage \_\_\_\_ GEM Pad plane





#### Hardware: Concept

- PCB of 9 x 9 cm<sup>2</sup>
- 3 pad sizes and different connection lengths to be tested, smallest pads with shortest connections directly on the chip
   → influence of capacitance
- 500 channels connected in total
- To be used with 10 x 10 cm<sup>2</sup> GEMs in a small TPC
- First prototype boards were delivered Jan-May, only 3<sup>rd</sup> production attempt successful





#### Hardware: Concept

- PCB of 9 x 9 cm<sup>2</sup>
- 3 pad sizes and different connection lengths to be tested, smallest pads with shortest connections directly on the chip
   → influence of capacitance
- 500 channels connected in total
- To be used with 10 x 10 cm<sup>2</sup> GEMs in a small TPC
- First prototype boards were delivered Jan-May, only 3<sup>rd</sup> production attempt successful
- Electroless Nickel Electroless Palladium Immersion Gold (ENEPIG) coating







Ulrich Einhaus | Particle Identification with the High Granularity TPC Readout ROPPERI | 28.11.2017 | Page 9

## Stud Ball Bumping (SBB) process

Gold stud bumping is an evolution of the  $\sim$  60 years-old wire bonding process. **Gold stud ball**: the wire is snapped off after the ball is initially connected to the substrate



 Low-cost process: direct deposition on Al pad (No UBM, lithography process)

Fast deposition: 20 bumps/s

 Short setup time: ideal for single die bump-bonding (i.e. prototype and R&D)



Gold Ball-wedge wire-bonding





Achieved Bump & pitch size

Au wire diameter (µm)	Bump diameter (µm)	Minimum pitch (µm)
25	60	100
15	30	50
12.5	23	35

KIT, Institut für Prozessdatenverarbeitung und Elektronik

## **Bonding process**



#### **Bonding parameters:**

Bond Force :~ 5 gr/bumps, Bond Temp.: ~very low, Bond Time : few minutes ~



#### Chip to PCB during the Bonding process



Cross-section of Gold Stud Bump-Bonding on CMS pixel detector

- Broken connections: no communication with chip, no data readout
- First time (?) bonding at 55  $\mu$ m pitch directly from silicon to a PCB
- Problem: different coefficients of thermal expansion (CTE):
  - Si ~ 2.5 ppm/K, FR-4 ~ 15 ppm/K
  - → over 14 mm and at 250°C: ~ 40  $\mu$ m offset
- Bond at 100°C
  - Worse metal diffusion
  - Still mechanical stress
- Got 1 reasonably good data set (of noise) before system broke again What can we learn from that?



### Hardware: Capacitance Challenge

- With growing input capacitance the signal to noise ratio goes down
- Timepix was developed C < O(100fF)</li>
- Capacitances: Pads: O(0.1pF) Lines: O(1pF/2.5cm) Bump bond connections: O(0.1pF)
- Gain for triple GEM stack: 2k-5k, potential for significant increase



X. Llopart: Timepix Manual v1.0



- Correlation between pad distance from Timepix and noise consistent with expectation
- Used threshold: 380 counts, typical: 300-400 counts, 1 count = 25 e-



• Large errors, but some confidence reg. noise assumptions



Ulrich Einhaus | Particle Identification with the High Granularity TPC Readout ROPPERI | 28.11.2017 | Page 14

#### Hardware: Flatness

- Sufficient flatness of few µm required for bonding
- Measured after chip came off

height distribution





Entries

201183



Ulrich Einhaus | Particle Identification with the High Granularity TPC Readout ROPPERI | 28.11.2017 | Page 15

#### Hardware: Flatness

- Sufficient flatness of few µm required for bonding
- Measured after chip came off
- Maps design file very well
- Central peak FWHM: 5 µm, areas without metalisation and gold studs visible







#### Hardware: Consequences & Outlook

- Ordered new boards of 2 types with lower CTE
  - Type A: regular material layered with copper-invar-copper (8 ppm/K) delivered, currently in equipping, bonded afterwards
  - Type B: different base material (12 ppm/K) expected in Dec.
  - Small TPC and readout is set up and ready for performance tests of ROPPERI prototype
- Flatness measured, sufficient for bonding, under continuous observation



### dE/dx in a TPC

- Energy loss measurement is an advantageous intrinsic capability of TPCs
- Via Bethe-Bloch curve in combination with momentum this leads to the identification of the particle species
- The measurement is usually done via charge summation
- Due to large fluctuations in each ionisation step like  $\delta$ -electrons the charge / distance distribution is Landau shaped  $\rightarrow$  large RMS
  - $\rightarrow$  mediocre correlation with energy loss





- The number of ionisation steps / distance is Poisson shaped
  → smaller RMS → better correlation → better particle identification
- Counting clusters allows for improved particle separation compared to conventional charge summation
- Depends on fraction of identified clusters (counting efficiency)
  → Need sufficient granularity to identify clusters!





Ulrich Einhaus | Particle Identification with the High Granularity TPC Readout ROPPERI | 28.11.2017 | Page 19

#### Cluster counting efficiency: ~25-30%



Ulrich Einhaus | Particle Identification with the High Granularity TPC Readout ROPPERI | 28.11.2017 | Page 20

#### Software

- Simulation and reconstruction chain: MarlinTPC within the ILCsoft framework
- Primary ionisation and drift of individual electrons → transfer IDs of respective clusters to match with hits later
- Digitisation incl. pixelated noise

Generate MCParticles
Primary Ionisation
Drift
GEM Amplification
Projection onto Timepix
Timepix Digitisation
Even and the fite
Export to .nts
Source Extractor
Source Extractor Import to .slcio
Source Extractor Import to .slcio Tracking: Hough Trafo



Simulation

- Cluster identification via external software 'Source Extractor' → returns 'hits' for tracking [http://www.astromatic.net/software/sextractor]
- Event display:
  - Green: electrons after drift
  - Red: digitised raw data 'heat map'
  - Blue: reconstructed hits
- Assign drifted electrons to hits
- match IDs, look for 'double uniques': all electrons from exac. 1 cluster go into exac. 1 hit
  - → get 'exact cluster-hit-identification' efficiency

Generate MCParticles
Primary Ionisation
Drift
GEM Amplification
Projection onto Timepix
Timepix Digitisation
Export to .fits
Source Extractor
Import to .slcio
Tracking: Hough Trafo
Analysis
e.g. cluster-hit
Identification



Simulation

Reconstruction Analysis

### **Cluster-Hit Identification Efficiency**

- Track length = 300 mm
- B = 1 T
- Lower limit on 'cluster counting efficiency'
- But what about separation power?

$$\rightarrow \qquad S = \frac{|\mu_{\pi} - \mu_{K}|}{\sqrt{\frac{1}{2}(\sigma_{\pi}^{2} + \sigma_{K}^{2})}}$$





#### **Pion-Kaon Separation Power**







UIRICH EINNAUS | Particle identification with the High Granularity TPC Readout ROPPERI | 28.11.2017 | Page 24

#### **Pion-Kaon Separation Power**





Extrapolation by sqrt(n) to ILD with track length = 1.2 m gives a separation power of 3.6 (with  $165 \mu \text{m}$  pads)

→ improvement to conventional charge based measure



UIRICH EINNAUS | Particle Identification with the High Granularity TPC Readout ROPPERI | 28.11.2017 | Page 25

#### **Pion-Kaon Separation Power**





Validity of scaling with sqrt(n) not certain

Extrapolation by combining events is compatible within errors

High statistics runs currently ongoing



UIRICH EINNAUS | PARTICLE IDENTITICATION WITH THE High GRANULARITY TPC Readout ROPPERI | 28.11.2017 | Page 26

- Proposal for a GEM-based high granularity TPC readout
- Significant improvement of integration together with possible enhancement of performance
- First boards showed challenge of bonding process, nonetheless delivered a first minimal data set
- New boards are in queue, setup is ready for detailed performance tests
- MC simulation show improvement in particle separation power compared to conventional dE/dx by charge
- There is room for further identification performance improvement



# Backup



### Idea: intermediate solution between pads and pixels



- Clusters contain the primary information of the ionisation
- For a GEM-based system: Can we find a solution to resolve clusters?
- What is the optimal pad size to
  - improve double hit and double track resolution,
  - do cluster counting for improved dE/dx?
    - → O(200µm)



### Idea: intermediate solution between pads and pixels



- Clusters contain the primary information of the ionisation
- For a GEM-based system: Can we find a solution to resolve clusters?
- What is the optimal pad size to
  - improve double hit and double track resolution,
  - Do cluster counting for improved dE/dx?
    - → O(200µm)



#### Former Tests with GEMs + pixels

- GEMs + Timepix, by Uni Bonn and Uni Freiburg
  - Charge depositions spread continuously over O(100) pixels (compared to Micromegas)
  - High gains (60k to 100k) necessary for signal/noise
- Large pixels by adding metal pads to chip



J. Kaminski: Measurements during the October test beam with the GEM-TPC and Timepix; at RD-51 meeting 2010



#### Former Tests with GEMs + pixels

- Clusters visible with large pixels  $\rightarrow$  How large can one go?
- Similar to our approach ۲ But: still need up to 120+ ۲ chips per module 4x4: 5x5: 220x220 µm<sup>2</sup> 275x275 µm<sup>2</sup> Utilize full chip! ۲ Utilize full anode area! 1x1: 2x2: 55x55 µm<sup>2</sup> 110x110 µm<sup>2</sup> 1×1 J. Kaminski: Measurements during the October test beam

with the GEM-TPC and Timepix; at RD-51 meeting 2010



### GEMs + pixels: event displays

Large pixels Timepix
 [ 5x5 | 4x4 ]
 [ 1x1 | 2x2 ]

25 cm Drift





#### **Cluster counting efficiency**

- Here:
  - He:CO<sub>2</sub> 70:30
  - Expected: 15.15 clusters/cm
  - Approaches without absorption 14.6 clusters/cm





### **Readout: Timepix**

- Advancement to the Medipix chip (RD51, CERN) with the capability for time measurement
- Geometry:
  - 256 x 256 pixels, 55µm pitch
  - 1.4 x 1.4 cm<sup>2</sup> active area
- Pixel floor plan: octagon: Al opening for input signal 1: preamplifier
  - 2: discriminator/digitisation
  - 4: configuration
  - 5: mode selection
  - 6: 14-Bit shift register (max. 11810)

X. Llopart: Timepix Manual v1.0







### **Readout: Timepix**

- Mode selection (per pixel) in 5:
  - "Time of arrival" (ToA) gives timing information
  - "Time over threshold" (ToT) gives charge information
  - For the Timepix3 (2<sup>nd</sup> generation) both modes can run simultaneously
- External reference clock with up to 100MHz / 10ns
- During a given shutter window the register counts and is read out afterwards (serial 10ms, parallel 300µs)









 Readout chain based on the Scalable Readout System (SRS) from CERN established



- Simultaneous modes "time of arrival" and "time over threshold"
- To be used after proof-of-principle
- Exchange of information and experience with photon science groups at DESY (member of Timepix3 collaboration)



### UNIMOCS prototype TPC



