Operational experience with the NA62 Gigatracker

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On behalf of the NA62 Gigatracker Working Group:
CERN, INFN Ferrara, INFN Torino, UCL Louvain

The 25th International Workshop on Vertex Detectors
La Biodola, 25-30 September 2016
Outline

- The NA62 experiment
- Gigatracker detector system
  - Requirements from the experiment
  - Sensor technology
  - The TDCpix front-end ASIC
  - Micro-channel cooling system
- Detector performance
  - Prototype detector
  - Detector commissioning in NA62
  - Detector performance in 2015/2016 runs
- Conclusions
NA62 experiment

- Measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at the CERN SPS
- Un-separated hadron beam (6% K, 23% p, 70% $\pi$)
- 75 GeV/c, $\Delta p/\langle p \rangle \sim 1\%$
- 0.75 GHz beam rate (~50 MHz K)

Total Length: 270 m

Target

Beam Pipe

KTAG

CHANDI

Charged Particle Veto

Gigatracker

Vacuum Tank

CHOD

Charged Hodoscope

LAV: Large Angle $\gamma$ Veto

SAV: Small Angle $\gamma$ Veto

RICH

LKr MUV

Straw Tracker

Decay Region: 65 m
Beam spectrometer
- Provides momentum, time and angular measurements on all beam tracks
- Sustains high and non-uniform rate (~150 MHz/cm² in the center, 0.75 GHz total)
- Reduces multiple scattering and beam hadronic interactions

- $X/X_0 \sim 0.5\%$ per station
- $\sigma(p_K)/p_K \sim 0.2\%$
- $\sigma(\theta_K) \sim 16$ μrad
- 300 μm × 300 μm pixel size
- **200 ps time resolution on single hits**
Gigatracker assembly

- Hybrid pixel detector
  - 300 \( \mu \text{m} \times 300 \mu \text{m} \) pixels
  - 1 sensor (\( \sim 6 \times 3 \text{ cm}^2 \)) bump-bonded to 10 read-out chips

- Material budget:
  - 200 \( \mu \text{m} \) sensor + 100 \( \mu \text{m} \) read-out chip \( \rightarrow \sim 0.32\% \, X_0 \)
  - Bump bonds \( \sim 0.01\% \, X_0 \)
  - Mechanical support and cooling \( \sim 0.15\% \, X_0 \)
  - **Total** \( < 0.5\% \, X_0 \)

- Minimization of material in active beam area
  - Beam profile adapted: two rows of read-out chips
  - Wire connections to R/O chip outside active area
Operating environment

- GTK stations installed in **vacuum**
- High and non-uniform radiation levels
  - Expected fluence is $\sim 2 \times 10^{14} \text{\,1\,MeV}\, n_{eq}/\text{cm}^2$ during one year of operation (~100 days) in the sensor center
- Efficient cooling necessary for stable detector operation
  - 35 W per station
  - Very low material budget ($\sim 0.15\%\ X_0$) in the active beam area
- Micro-channel cooling plate chosen by the NA62 collaboration
Sensors and bump-bonding

- 200 μm thick p-in-n and n-in-p planar sensors (FBK, CiS)
- Over-depleted operation of the detector required to achieve target time resolution (300 V over-bias)
  - Fast charge collection
- Irradiation of test structures
  - Annealing study following expected run scenario

- Flip-chip bonding and read-out wafer thinning (100 μm) done at IZM
  - Benzocyclobutene (BCB) deposition
## Read-out specifications

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<th>Specification</th>
<th>Value</th>
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<td>Dissipated power</td>
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*Talk by M. Noy on “Chip Development for High Time Resolution Silicon Detectors”*
Simplified pixel architecture

- IBM 130 nm CMOS technology
- On-pixel fast preamplifier and discriminator
  - 65 mV/fC gain, 5 ns peaking time
- Asynchronous transmission lines from pixels
- Data driven architecture
- ENC \( \sim 210 \text{ e}^- \) (170 e\(^-\) with no sensor)
- 5 bit DAC thresh. trim
- Polarity control
- Pixel mask
- TX with pre-emphasis
TDCpix architecture

- 1800 pixels (40 × 45), 300 × 300 µm²
  - Asynchronous
- End-of-Column (EoC)
  - Per-pixel hit signal to EoC
- 360 dual TDC channels
  - TDC Bin size 98 ps
- Self-triggered operation
  - 210 MHits/s rate
  - 4 × 3.2 Gb/s serializers
- SEU protection
  - Triplicated digital logic
- No digital activity in the matrix
Time-to-digital converter

- Digital signal from 5 pixels in a column (45 pixels) are sent to a “hit arbiter”
- A TDC pair is connected to each “hit arbiter” to measure leading and trailing edge
  - 360 TDC pairs/chip
  - 9 TDC channels per column
- Dual edge stamping
  - Time Over Threshold
- Delay Locked Loop
  - 320 MHz reference
  - 32 bins of ~98 ps
- Shared between two TDCs
Cooling system

- Constraints
  - Material budget minimization ($<0.5\% \, X_0$)
  - Detector in vacuum
  - 35 W power dissipated per station
- Micro-channel cooling matches the constraints
  - Etch channels (+ openings for inlets/outlets) in a 140 $\mu$m (210-280) thick plate glued to bump-bonded assembly
  - Circulate coolant ($C_6F_{14}$) in micro-channels
    - 3.5 bars pressure, 3 g/s flow
    - Two cooling circuits
    - Temperature down to -25 °C
- First application of this technique to a HEP experiment
Micro-channel cooling

- Fabricated by CEA Leti
- 200µm × 70µm channels
Micro-channel cooling

- Fabricated by CEA Leti
- 200µm × 70µm channels
- Two cooling circuits
Micro-channel cooling

- Fabricated by CEA Leti
- 200µm × 70µm channels
- Two cooling circuits
- Fluid brought in with capillaries
- Kovar connectors soldered onto cooling plate
Micro-channel cooling

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- 200µm × 70µm channels
- Two cooling circuits
- Fluid brought in with capillaries
- Kovar connectors soldered onto cooling plate
- Infra-red picture
Electro/mechanical integration

- Detector glued on 150 μm (210 μm) cooling plate

Sensor
TDCPix    TDCPix
Electro/mechanical integration

- Detector glued on 150 μm (210 μm) cooling plate
Electro/mechanical integration

- Detector glued on 150 $\mu$m (210 $\mu$m) cooling plate
- Cooling plate clamped on PCB, then TDCPix wired bonded to PCB (14 layers)
  - Serving power, clock, config. and receiving data
  - 40 differential 3.2 Gb/s signals over 30 cm
  - 73 $\mu$m bonding pitch on chip
Electro/mechanical integration

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  - 73 μm bonding pitch on chip
- PCB glued on frame + flange
- Flange closes the vacuum
- Easy access for interventions
GTK back-end Read-Out

- TDCpix sends out every hit: trigger matching needed
- GTK-RO built using FPGA (Altera Stratix GX110)
- Each GTK-RO made of two decked cards: daughter card handles interface with TTC
- Each TDCpix is connected to one GTK-RO through 4 optical links (one per 3.2 Gb/s serializer) plus 1 configuration link
  - Trigger matching efficiency measured splitting optical signal and reading trigger-less data concurrently (on few boards)
- GTK-RO board must:
  - Buffer data, waiting for level-0 trigger decision (maximum level-0 trigger latency is 1 ms)
  - Retrieve data in a 75 ns time window upon trigger request
  - Send data to the subdetector PC
Laser test setup

- IR light (1060 nm) to create charge carriers through silicon bulk
- Characterize GTK bump-bonded assemblies on laboratory bench

- 5 ps time precision
- Absolute calibration of injected charge
  - Radioactive sources (\(^{241}\)Am, \(^{109}\)Cd)
Results from laser tests

- Time resolution of ~75 ps at 3 fC (average charge created by minimum ionizing particle)
  - Charge injected at the pixel center

- X-Y position scan of pixel matrix
  - Variation of measured time with impact position inside pixel
  - Geometrical effect (weighting field)

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Test-beam at CERN

- Test-beam at the T9 beam-line (CERN PS East Hall)
  - 10 GeV/c $\pi^+$ and $p$
- 4 consecutive **prototype** detector planes
- Fast scintillators used for timing reference
  - Synchronized 25 ps TDC independent read-out
- Very precise mechanical supports and pre-alignment at the 150 $\mu$m level
- Operation in air (no cooling, no dry air circulation)
- Results published on *JINST* 10 P12016 (2015)
Time-walk correction

- Time-walk correction evaluated using fast scintillators for time reference and time-over-threshold information
  - Pol fit or look-up table

- Discriminator thresholds set by unique digital-to-analog converter for all pixels
  - \((0.70 \pm 0.14) \text{ fC}\)

- Time resolution after correction is \(~160\) ps (for 300 V bias)
Bias voltage variation

- Time resolution measured as a function of bias on prototype detector
- Better than **150 ps** at 400 V
  - Still room for improvement at higher voltages
TDCpix assemblies

- Bump-bonded assemblies with final TDCpix ASIC
  - Full assemblies (1 large sensor + 10 read-out chips)
  - Single-chip assemblies opened and closed back-side metallization
- For lab bench and laser tests
Installation in NA62 beamline

- All stations and infrastructure installed in 2014/2015
- Beam line commissioned up to nominal intensity
- Sub-detectors and trigger/DAQ up to 20% nominal intensity
- Gigatracker commissioned in 2014/2015
  - GTK cooled at 0 to -10 °C
  - Thresholds set to 0.7 fC
  - Bias voltage set to 100-300 V depending on running periods
Hit maps

Hit Map GTK1 - 2016

Hit Map GTK2 - 2016

Hit Map GTK3 - 2016
Time resolution (1)

- Preliminary results from 2015 data
  - Paper on NA62 detector and beam line performance is under preparation
- Time walk correction using KTAG as timing reference

![Graph showing time resolution analysis](image)
Time resolution measured using 2015 data

- 300 V bias except for GTK3 (200 V)

- Further calibrations and data analysis needed to exploit the full potential of the detector
Important contribution of the Gigatracker to improve missing mass resolution

Preliminary results from 2015 low intensity data

**Graph:**
- **NA62 preliminary - 2015 data**
- **Graph:**
  - $m_{\text{miss}}^2$ vs. $P_{\pi}$ [GeV/c]
  - NA62 Preliminary 2015 Data
  - Data with GigaTracker
  - Data without GigaTracker
  - Expected (proposal)
  - Expected $P$ resolution
  - Expected $2\pi$ resolution
  - Expected $K^*$ resolution
  - Expected $\phi$ resolution
  - Expected $K$ resolution

**Equation:**
$$m_{\text{miss}}^2 = \text{resolution}$$
Conclusions

- The Gigatracker detector is essential to measure BR($K^+\rightarrow\pi^+\nu\bar{\nu}$) at NA62
- Detector fully commissioned
- Excellent timing performance measured on thin hybrid pixel detectors (200 $\mu$m planar sensors) with a very high density of channels (18000 per sensor) in vacuum
  - High over-depletion necessary
- Innovative and very-low mass cooling plate based on micro-channels
  - First implementation in HEP experiment
- Analysis of full 2015 and 2016 data sets is on-going
  - Monitoring radiation damage effects on performance
Carriers drift velocity

- In “nominal” conditions we apply 300 V over 200 $\mu$m
- Electric field $1.5 \times 10^4$ V/cm
- Close to saturation but still room for improvement

![Carriers drift velocity in silicon (T=300 K)](image)

Legend:
- **electrons**
- **holes**

Institute for Nuclear Physics (INFN)

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VERTEX2016

Massimiliano Fiorini (Ferrara)
In timing measurements the slope-to-noise ratio has to be optimized rather than the signal-to-noise ratio alone.

- Very low r.m.s. noise \( \sigma_n \)
- Very steep signal at threshold level \( (dV/dt)_{thr} \)

Time resolution is given by the ratio: \( \sigma_t = \frac{\sigma_n}{(dV/dt)_{thr}} \)

Many contributing factors to consider:

- Need large signals, and fast “signal collection”
- Reduce input capacitance, match amplifier bandwidth
- Electric (weighting) field uniformity
- Energy release (total, straggling, direction)
- Time-walk correction
- Digitization (e.g. TDC bin size and linearity)
- ...

\[ \sigma \]

\[ \sigma_n \]

\[ (dV/dt)_{thr} \]

\[ \sigma_t = \frac{\sigma_n}{(dV/dt)_{thr}} \]
Time-walk correction

- To achieve excellent timing accuracy, a careful time-walk compensation has to be applied:
  
  Some alternatives:

- Single threshold discriminator and Time over Threshold
  - Time-walk correction algorithm based on the signal time over threshold (pulse width), obtained by measuring leading and trailing edges of the pulse
  - Accurate calibration needed to define correction algorithm

- Use of a Constant Fraction Discriminator (CFD)
  - Analog signal processing technique of time information
  - Single time measurement, complicated analog design

- Digitizer

- Multiple thresholds discriminator
Sensor signal

- Simulation of energy deposited in 200 µm silicon
  - GEANT4
- Most probable energy: 54 keV
  - 15 k e·h, 2.4 fC
- Mean energy: 72 keV
  - 20 k e·h, 3.2 fC
Complete electrical characterization of the full-chain (pixel $\rightarrow$ TDC $\rightarrow$ output)
- Scan over the full clock period for each charge
- Resolution better than 65 ps at 2 fC
Prototype read-out ASIC

- IBM 130 nm, 2.8 mm × 6.7 mm total size
- 320 MHz reference clock
- 60 pixels divided into 3 groups
  - 45 pixels with 9 read-out blocks, each one serving the 5 pixels through the “hit arbiter” block
  - Small array: 9 pixels
  - Test column: 6 pixels with analog output
- Extensively characterized with electrical tests, laser and particle beams
Time walk effect

- Peaking Time = 5 ns
- Time Walk
- Time Over Threshold
- "Leading"
- "Trailing"

Graph showing T1 and T2 vs Qin, Trise=2.5ns

- Qth=0.5fC
- Qth=0.6fC
- Qth=0.7fC
- Qth=0.8fC
- Qth=0.9fC
Prototype time resolution

- Time resolution measured for all 45 pixels per chip
  - Shown for 300 V bias
  - Variations mainly due to pixel-by-pixel threshold variation

- Clear threshold dependence
  - Worse resolution for small threshold values (smaller signal slope)
Prototype efficiency

- Track fitting and extrapolated track impact position to the target detector calculated
- Very high efficiency (>99%)
  - Pixels in the outer region and dead pixels have been excluded (red hatched area)
Contributions to $\sigma_{\text{time}}$

- Electronic noise from front-end chip
  - Measured $\sim 210$ e$^-$(ENC) with sensor
- Sensor bias voltage and threshold
  - Variation of charge collection time (signal slope at the discriminator threshold)
- Impact position on pixel sensor
  - Weighting field variation (geometrical effect)
- Total energy release
  - Variation of total energy released in sensor according to Landau/Vavilov distributions
- Energy straggling in the sensor bulk
  - Non-uniform energy release along track and delta rays
Sensor: signal formation

- Ramo-Shockley theorem
  - \( i = q \, v \cdot E_w \)

- Example:
  - Uniform release of 2.4 fC (MPV) along a 200 \( \mu \)m thick planar sensor
  - Assuming uniform weighting field
Sensor: weighting field effect

- Uniform charge release along the sensor thickness
- Charge injection at pixel center and close to the edge
Sensor: energy straggling (1)

- Energy released as a function of depth in silicon
- 200 µm thick silicon divided in 200 layers (1 µm each)
- GEANT4

An example

Energy released in the layers

<table>
<thead>
<tr>
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<tr>
<td>0.0005</td>
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</tr>
<tr>
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</tr>
<tr>
<td>0.002</td>
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<tr>
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</tr>
<tr>
<td>0.003</td>
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<td>0.0035</td>
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EnergyZ23

- Entries: 200
- Mean: 111.2
- RMS: 60.28
- Underflow: 0
- Overflow: 0
- Integral: 0.0556
- Skewness: -0.3244
Sensor: energy straggling (2)

- Total charge release of 54 keV (2.4 fC)
- One δ ray emitted at 100 µm
- δ ray energy is 10 keV (~0.4 fC)
NA62 Trigger and DAQ

- **L0**: Hardware synchronous level
  - 10 MHz to 1 MHz, 1 ms max. latency
  - Primitives (MUV, RICH, LAV, LKR)

- **L1**: Software level
  - “Single detector”, 1 MHz to 100 kHz

- **L2**: Software level
  - “Complete information”, 100 kHz to 10 kHz
Micro-channel cooling

Microelectronic Engineering
145 (2015) 133–137
Gigatracker carrier card
GTK-RO board
The $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay

- FCNC loop process

- Ultra-rare decay:
  - $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$ (SM prediction)

- Theoretically very clean: hadronic matrix element can be related to measured quantities

- Sensitive to new physics

- Existing measurement based on 7 events (E787/E949)
  - $\text{BR} = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$

- The NA62 Collaboration aims to measure $\mathcal{O}(100)$ $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events with $\sim 10\%$ background at the CERN SPS in few years of data taking
Signal and background

- Weak signal signature
  - $K^+$ track in, $\pi^+$ track out

- Backgrounds:
  - $K^+$ decay modes
  - Beam-gas and upstream interactions

- Experimental principles:
  - Kinematic reconstruction: $m_{\text{miss}}^2 = (P_K - P_\pi)^2$
    - Precise measurement of $K$ and $\pi$ momenta
    - Minimize multiple scattering
  - PID: $K$ upstream, $e/\mu/\pi$ downstream
  - Hermetic $\gamma$ detection
  - Sub-ns timing
Scheme for analysis

- **Signal selection**
  - 1 track with $15 \text{ GeV}/c < P_\pi < 35 \text{ GeV}/c$ and $\pi$ PID in RICH
  - No $\mu$ in MUVs; No $\gamma$ in LAV, LKr, IRC, SAC
  - 1 beam particle in Gigatracker with K PID by KTAG
  - $Z_{vtx}$ in 65 m fiducial volume

- **NA62 goal**: 100 signal events with $\sim10\%$ background
  - With $\sim10\%$ acceptance (3\% + 9\%), need $10^{13}$ $K^+$ decays and about $10^{-12}$ background rejection