The NA62 GigaTracker

M. Perrin-Terrin

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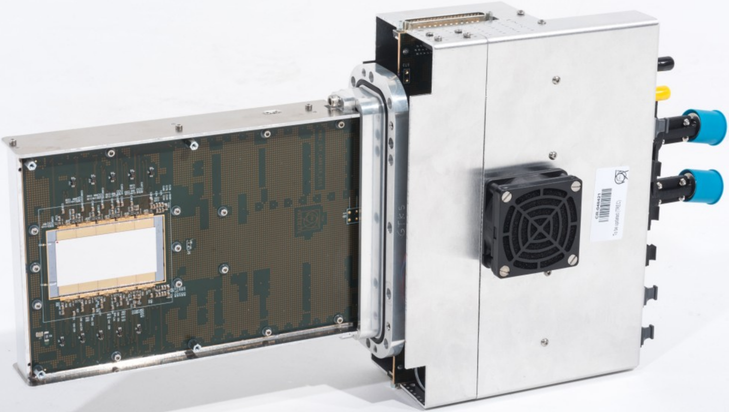
Mathieu PERRIN-TERRIN on behalf of the GTK Group

CERN, UCL Louvain, Università/INFN Ferrara, Università/INFN Torino



Outline

- **The NA62 Experiment**
- **The GigaTracker**
  - Overview
  - Pixel Matrix
  - Electro-Mechanical Integration
  - Cooling
- **Performances**
  - Kinematics
  - Time-stamping resolution

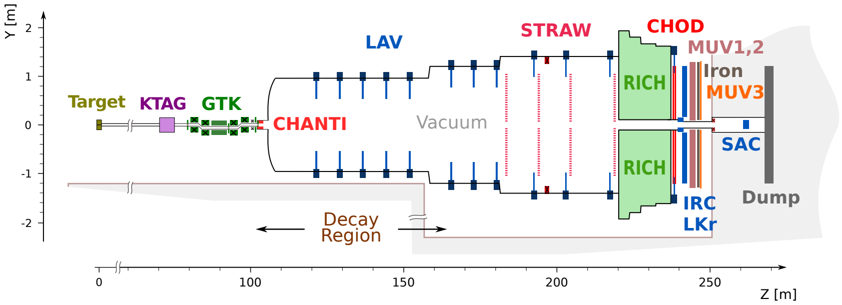
The NA62 Experiment

Goal: $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ with 10% precision

- **Challenging**: $\mathcal{B} = (8.4 \pm 1.0) \times 10^{-11}$ in SM & 2 neutrinos in final state
- **Previous results** by E787 (BNL) using **stopped beam**

NA62: decay in flight technique at CERN-SPS

- Continuous beam 750 MHz (6% K^+, 24% p, 70% π^+) at 75 $\mathrm{GeV/c}$
- **Decay in flight** technique, requires **beam spectrometer**: GigaTracker



Outline

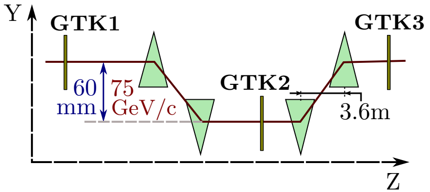
The GigaTracker (GTK)

Beam Spectrometer

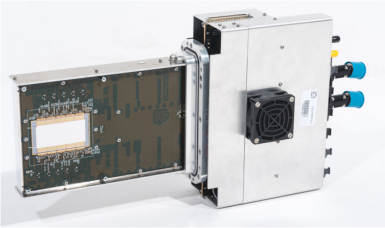
- Measures momentum, angle and time-stamp of **all beam track**
- Sustains high **particle flux**
- Minimized **material** budget

Design

- Three planes of Si **hybrid pixels**
- Installed in beam pipe **vacuum**: 10^{-6} mbar
- Replaced after 1 year at full intensity

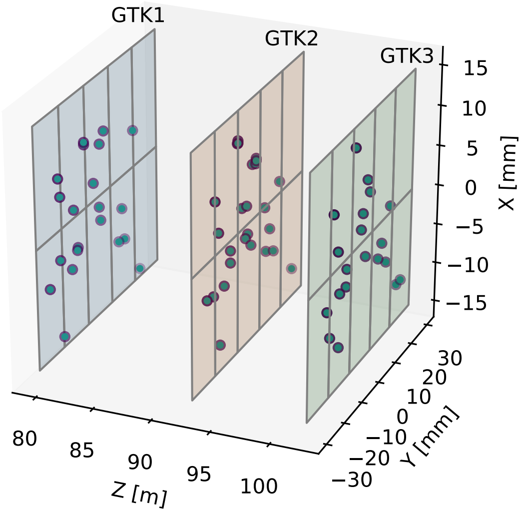


Beam Rate	800 MHz - 1 GHz 1.3 $\mathrm{MHz/mm^2}$
Peak Radiation	4.10^{14} 1MeV $\mathrm{n_{eq.}/cm^2}$ for 200 days
Efficiency	99%
Momentum Resol.	0.2%
Angular Resol.	16 µrad
Pixel Time Resol.	$<$ 200 ps RMS
Material Budget	0.5% X_0



The need of time-stamping

- **Association with other detectors** based on time-stamps
- Tracking in GTK relies on hit time-stamp (**4D Tracking**)



Typical Event at 35% beam intensity

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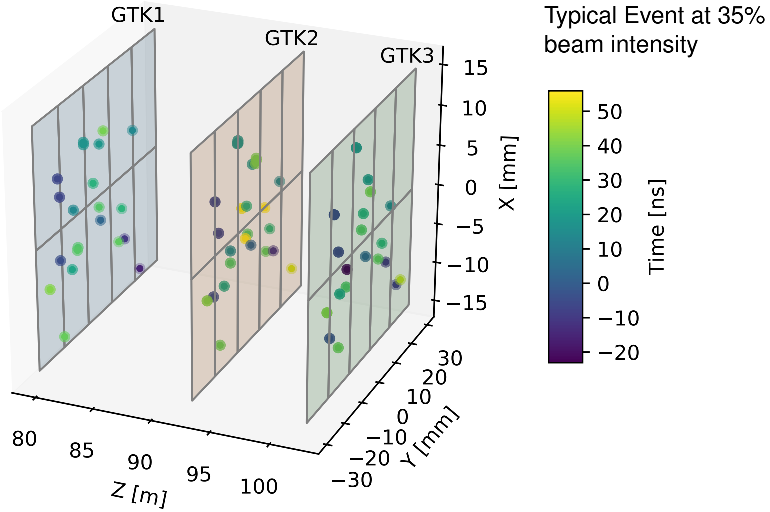

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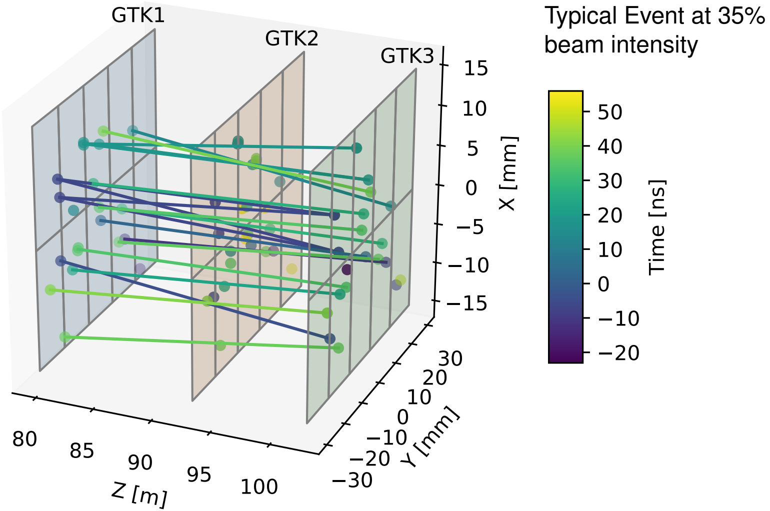
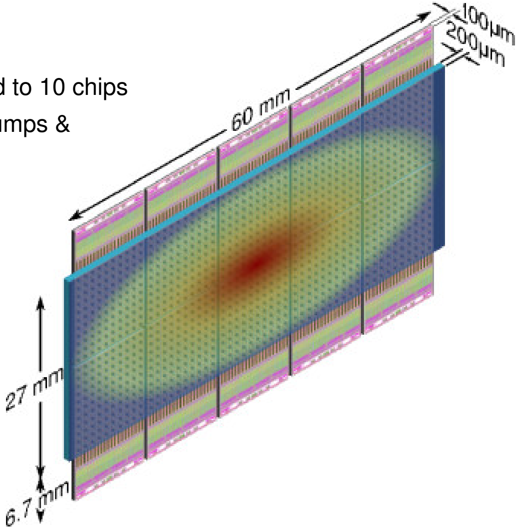


The Pixel Matrix

Hybrid Pixels

- 18'000 pixels of 300 $\times$ 300 μm^2
- Single 3 $\times$ 6 cm^2 sensor bonded to 10 chips
- Bump-Bonding (IZM): Sn-Ag bumps & Benzocyclobutane deposited to avoid discharges
- Sensor Type: n-in-p and p-in-n



Material Budget: 0.5% X_0:

- 200 μm of sensor
- 100 μm of asic
- 200 μm of support & cooling (Silicon microchannels)
- Wire bonding outside beam footprint

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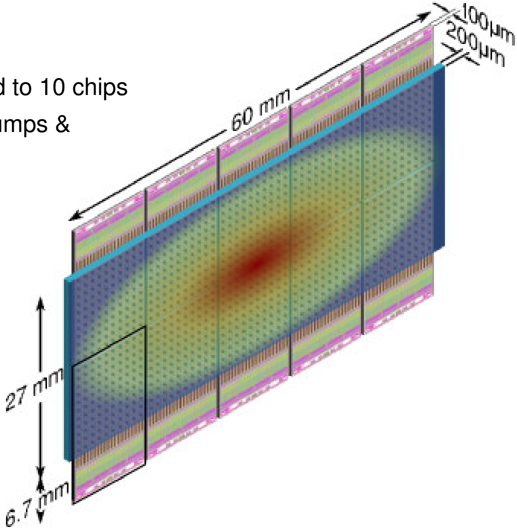
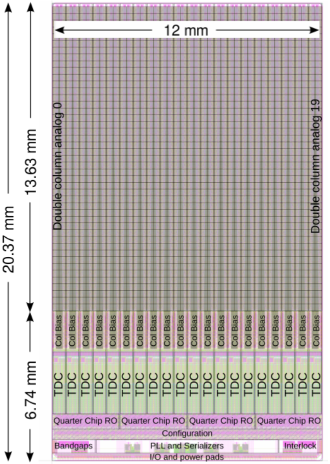


The TDCPix ASIC



Specifications

Time-stamp Resol	$< 200\,\mathrm{ps}$
Peaking Time	$5\,\mathrm{ns}$
Dose	$10^5\,\mathrm{Gy/y}$
Max Pixel Hit Rate	$140\,\mathrm{kHz}$
Chip Part. Rate	$150\,\mathrm{MHz}$
Data Ouput Rate	$12.8\,\mathrm{Gb/s}$
Power	$4.1\,\mathrm{W}$
Dynamic Range	$0.6 - 10\,\mathrm{fC}$
Efficiency	$> 99\%$

Architecture

- IBM 130nm CMOS technology

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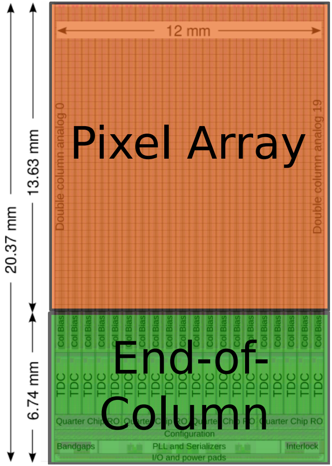

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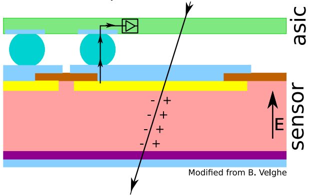
Architecture

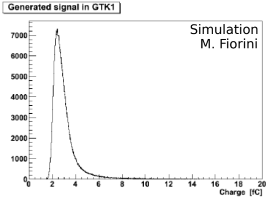
- IBM 130nm CMOS technology
- Digital logic fit in EoC to reduce digital switching noise in pixel array

Pixel Array

Signal Shaping

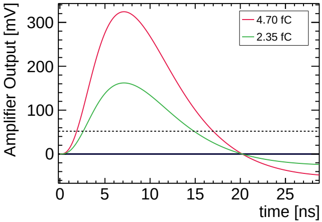
- **Pre-amplifier** (65 mV/fC, peak time: 5 ns) & **Discriminator** (5 bit DAC trim threshold)





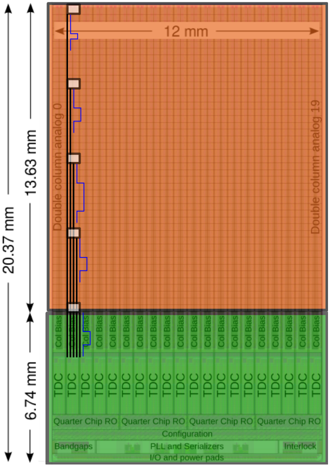
How to reach 200 ps time-stamp resolution?

- Sensor **over-depleted** (100-300 V bias) for fast charge collection
- **Charge release** is stochastic: Landau (Most Prob. Value of 2.4fC)
- Induced a **time-walk** depends on amplitude: record ToT for TW corrections



End-Of-Columns

Time-stamping of rising and falling **edges** performed at the end-of-columns



- SEU protected by **triplicating digital logics**
- **Digital Signal** from 5 pixels of a column are sent to a **multiplexer** (HitArbiter)
- Each HitArbiter is connected to a **Time to Digital Converter pair** (rising, falling edges)
- 360 TDC pairs in each chip
- **TDC** bin is 97 ps

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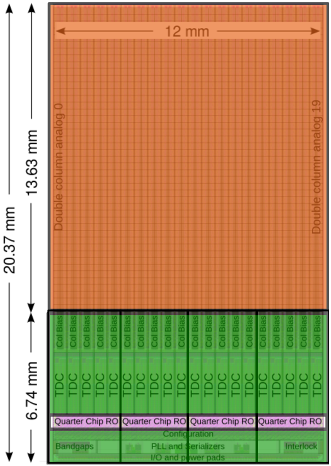

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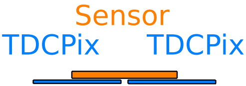
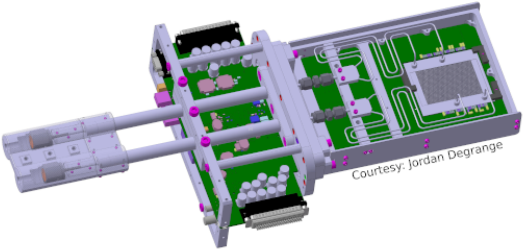
- 360 TDC pairs in each chip
- **TDC** bin is 97 ps
- **Self triggered** architecture
- Data sent out at 12.8 Gb/s with four **serialisers**

Mechanical Integration

- **Detector** is taped onto 200 µm silicon micro-channel **Cooling Plate**





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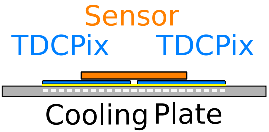

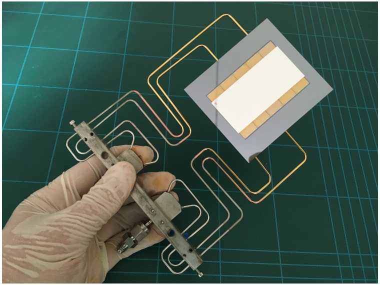

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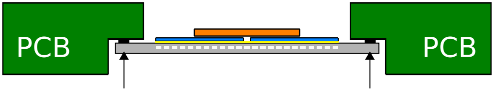

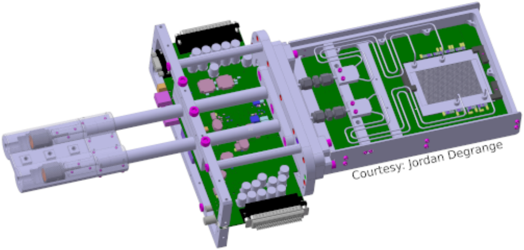

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- **Detector** is taped onto 200 μm silicon micro-channel **Cooling Plate**
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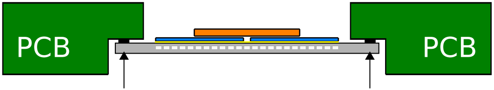
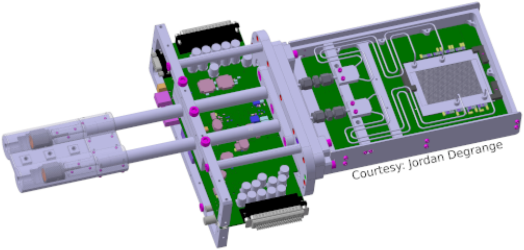
- **PCB** is mounted into frame and glued in **flange**





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- **Cooling Plate** is clamped onto **PCB** (isostatic)
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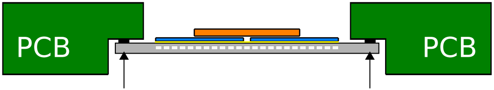
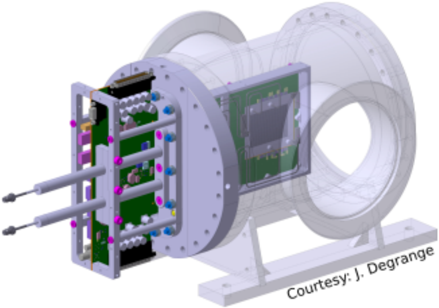
- **Flange** closes the **vacuum vessel**
- **Fast** mounting/dismounting for **station replacements**

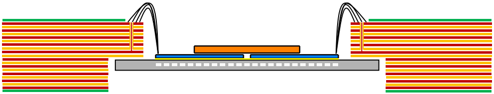


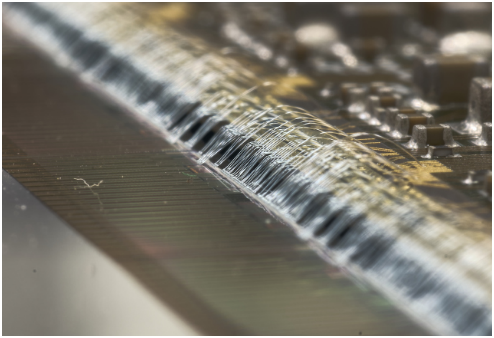


Electrical Integration

Wire Bonding

- TDCPix **wired bonded** to PCB
- Dense bonding scheme with 73 μm pitch on TDCPix
- Power, Clock, Config, Data transmitted



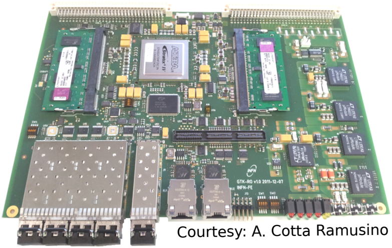


PCB

- 14 layers
- 40 differential 3.2 Gb/s signals over 30cm

Trigger and Data Acquisition

- Data sent **triggerless** to 30 DAQ boards called **GTK-RO**
- Each GTK-RO is connected to one TDCPix through 4 $\times$ 3.2 $\mathrm{Gb/s}$ links
- GTK-RO **installed in surface** (no radiation) & connected with 200 m long fibers to the detector
- Triggers and clock received on **daugther card**
- **Trigger matching** logic implemented with **FPGA** (stratix GX110)
  - DAQ Board **buffers data** for 1ms..
  - .. and **retrieves 75ns slices** upon each trigger request



Courtesy: A. Cotta Ramusino

Detector Cooling

Constraints

- Physics performances require to minimise **material budget**
- Detector in **vacuum**
- $\sim$**40W** power is dissipated per station

Detector Cooling

Constraints

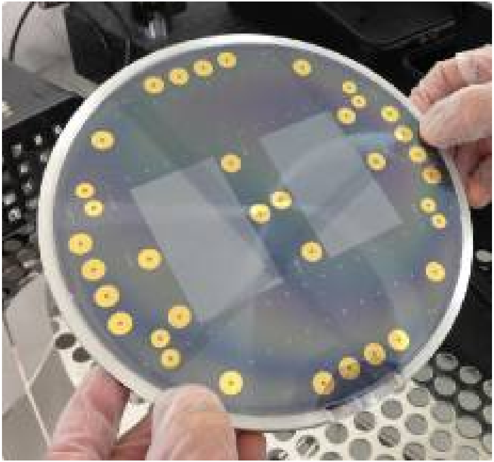
- Physics performances require to minimise **material budget**
- Detector in **vacuum**
- ~**40W** power is dissipated per station

Micro-channel cooling matches the constraints

- Etch **channels** in a 200 - 350 μm thin **Si plate** glued on TDCPix
- **Circulate coolant** (C_6F_{14}) in micro-channels
  (pressure 3.5 bars, flow 3 g/s, temp. ambient to -15C)
- **First implementation** in HEP (now also in VELO)

Cooling Plates

- Fabricated by **CEA Leti**



Cooling Plates

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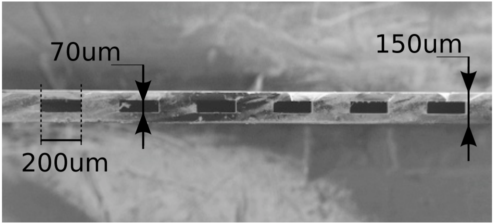
- **200µm× 70µm channels**



Cooling Plates

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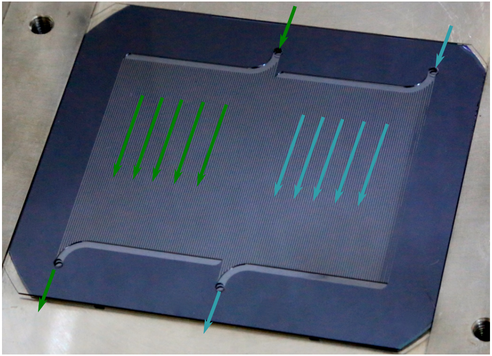
- Two cooling **circuits**



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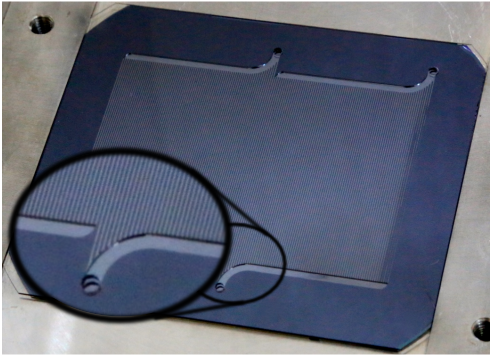
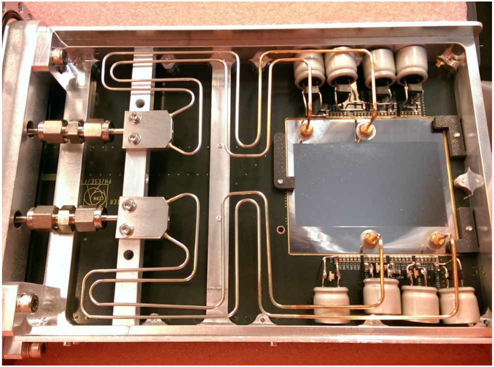


Cooling Plates

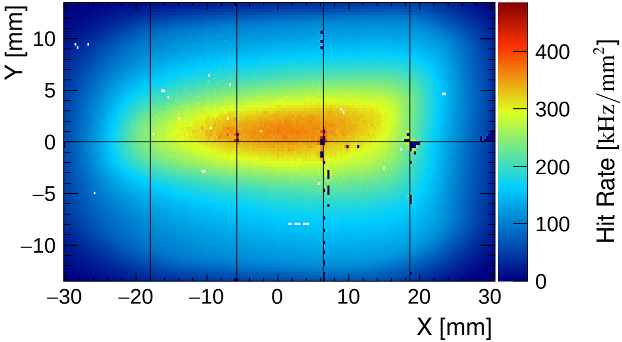
- Fabricated by **CEA Leti**
- **200μm$\times$ 70μm channels**
- Two cooling **circuits**
- Fluid brought in with **capillaries**
- Kovar **connectors** soldered onto cooling plate



Outline

GTK fully operational since 2016

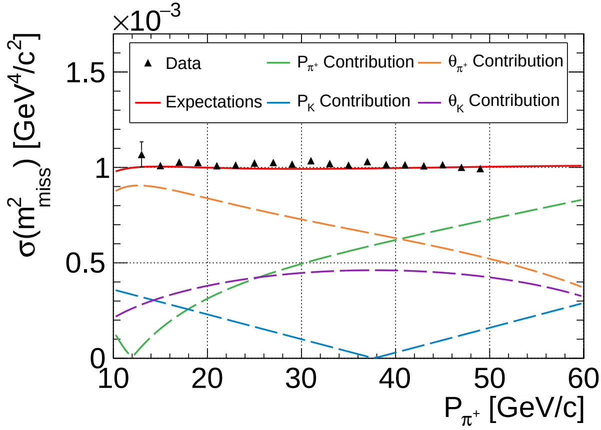
- Fully operational since September 2016
- Few noisy/dead pixels ($<$ 100 per station) at the end of 2017
- Beam intensity around 35% (60%) of nominal in 2016 (17)



Kinematics

Kinematics

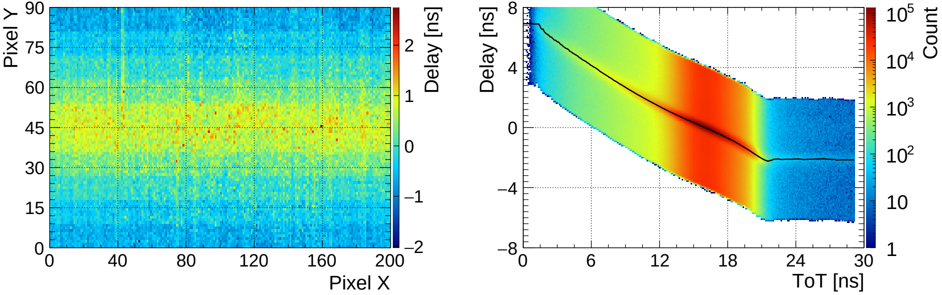
- Physics performance **matches design** performance
- Resolution of squared missing mass $|p_{K^+} - p_{\pi^+}|^2$ of $K^+ \to \pi^+ \pi^0$



Time Calibration

Time-stamp corrections

- Individual **pixel delay** (54k)
- Chip **time walk** (1 delay per ToT bin)
- **Reference time**: KTAG (70 ps resolution)



Time Resolution at Sensor bias of 100 V

Conditions

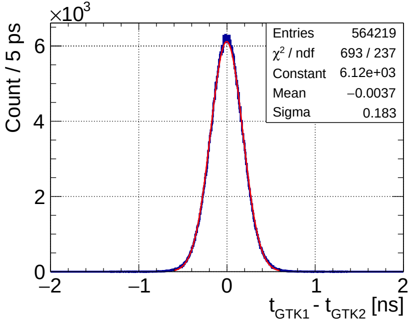
- **At detector installation** in 2016
- Sensor Type: **n-in-p**
- Operation **bias:** 100 V

Two Measurement Methods

- Timestamps difference between GTKs KTAG RICH ($\sigma_t < 100$ ps)
- Timestamps difference between the 3 GTK stations

Results

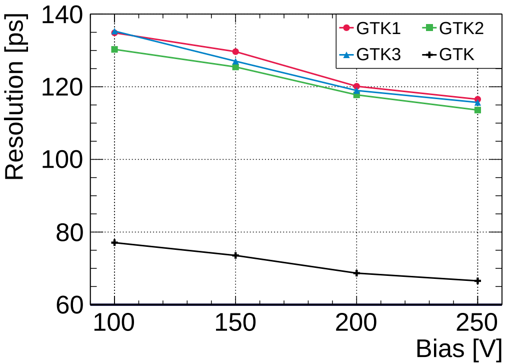
- **Hit resolution:** 130 ps
- **Track resolution:** 75 ps
- Design resolution matched



GTK1	132.0 ps
GTK2	127.1 ps
GTK3	129.2 ps

Bias Voltage Scan

- Data collected at **end of 2016 run**, with **n-in-p** sensor
- 65 ps track time-stamp resolution at 250 V!



- **Weak improvement** (15%) of the time resolution from 100 V to 250 V
- Charges collected faster but TDCPix pre-amplifier peaking time is fixed (5 ns) and larger than collection time

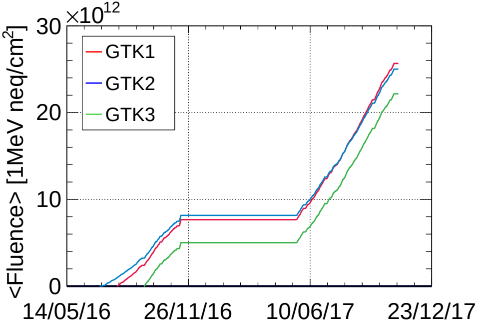
Stability over 2016 and 2017

Conditions

- New detectors installed during the 2016 run
- Dismounted and **stored at $-25\,\mathrm{C}$** between 2016 and 2017 runs
- Re-installed for 2017 run

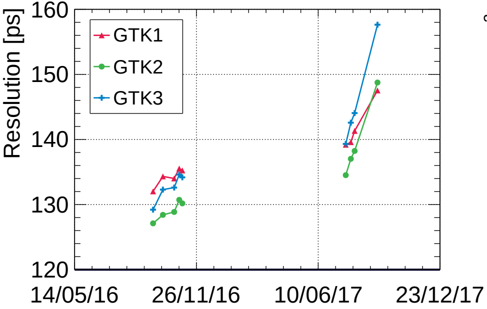
Irradiation

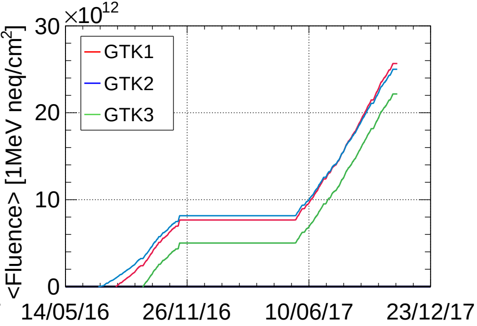
- Average Integrated **Fluence**: $2.5 \times 10^{13}\ 1\,\mathrm{MeV\ eq.\ n/cm^2}$
- **Peak Fluence** 5 times higher ($1.25 \times 10^{14}\ 1\,\mathrm{MeV\ eq.\ n/cm^2}$)



Time Resolution Stability over 2016 and 2017

- **Degradation** of time resolution of up to 25 ps (20%)
- Performances **still better than design** ones
- **Origin** not fully understood as many even occurred over 1.5 year
- **Radiation** is certainly a degradation factor





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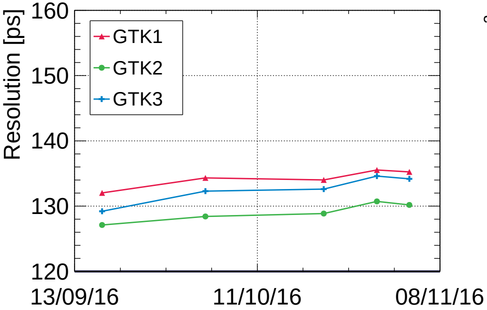

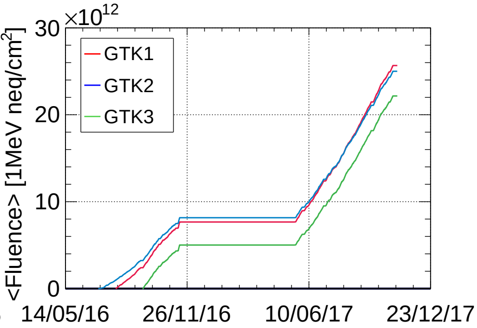

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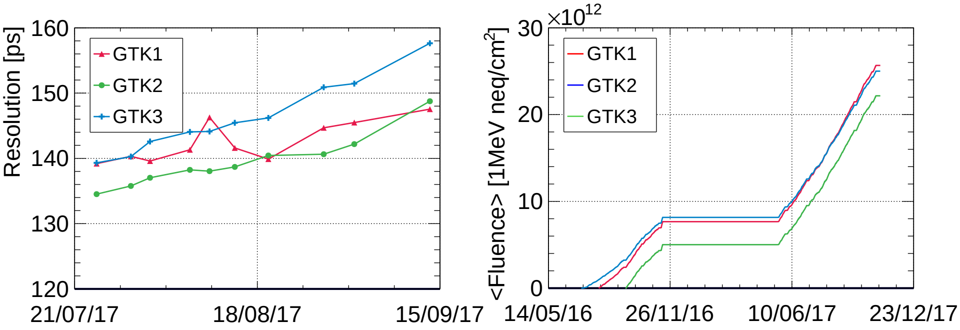


Outline

Conclusions and Prospects

Summary

- The GigaTracker is the NA62 **4D beam tracker** and is essential to measure $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$
- The detector is **fully operational** since 2016
- **Excellent time resolution** are achieved: 130 ps for single hit, small degradation over time
- Innovative **low mass cooling** plate with silicon micro-channel was implemented (now used for other detectors like LHCb-VELO)

Prospects

- **2018** data being processed
- NA62 is preparing to run **after LS2**
- GTK **production** keeps going!

Extra Slides

5 Efficiency

6 Time-Stamp Resolution

7 Noise

8 Leakage Current

Outline

Efficiency

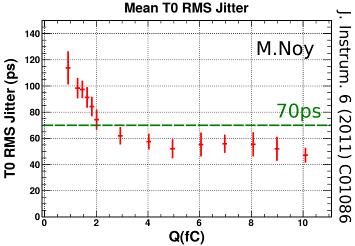
- Efficiency evaluation is not obvious
- Overall Efficiency is 96%:
- 3% due to GTK-RO:
  data sent by frame of 6.4 μs. When hit rate is high, hits words are send in the next frame. GTK-RO performs trigger matching on one frame only
- 1 to 1.5% due to the 3 GTK Stations

Outline

Time Resolution - TDCPix Demonstrator

Charge Injection

- **Laser** pulse shined at pixel centre
- Time resolution: **70 ps** RMS for charged injected equivalent to MIP



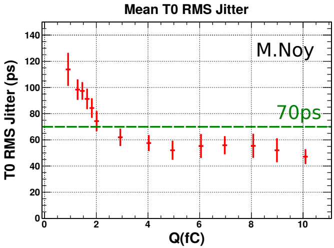
Time Resolution - TDCPix Demonstrator

Charge Injection

- **Laser** pulse shined at pixel centre
- Time resolution: **70 ps** RMS for charged injected equivalent to MIP

Beam Test

- π^+ at $10\mathrm{GeV}/c$ at CERN PS in 2012
- Time resolution: **200 ps** RMS



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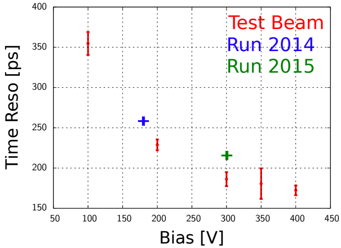

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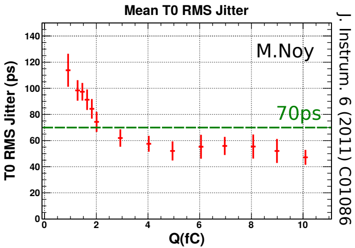
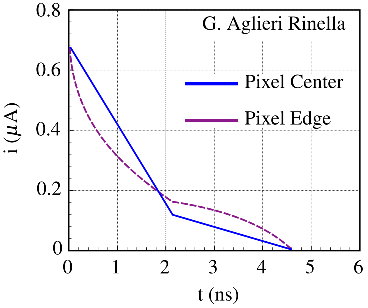
Difference Beam/Laser

- Weighting field and charge straggling
- Time resol. as function of hit position (Laser, Demonstrator)





Time Resolution - TDCPix Demonstrator

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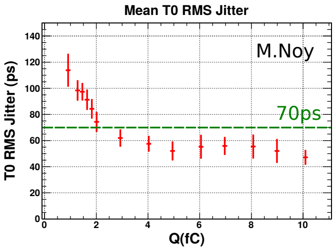
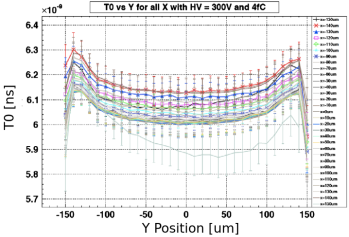


J. Instrum. 6 (2011) C01086



Nucl. Inst. A 718 (2013)

Time-stamp resolution breakdown

For TDCPix Demonstrator based on laser test and beam test we had:

- 75 ps from the chip
- 85 ps from field variable at pixel edge
- 60 ps charge straggling

Same study has to be redone for the final TDCPix

Outline

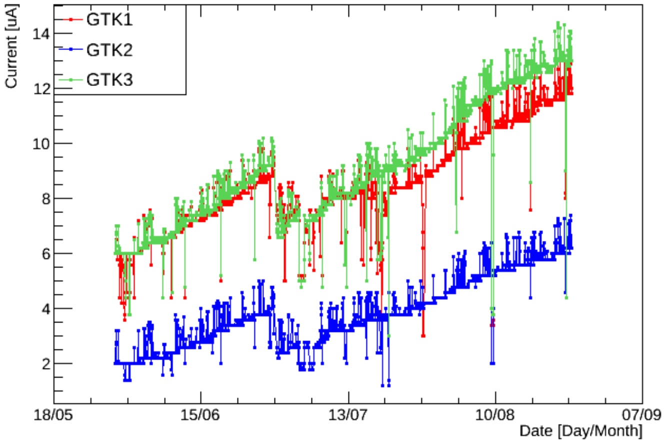
Noisy Pixels

- In 2015, intermittent noise (250 kHz) developed on many pixels (max nominal hit pixel rate expected at 140kHz)
- TDCPix X-ray irradiation unable to reproduce it
- Not reproduced either with 2016 detectors
- 3 differences (n-in-p vs p-in-n, BCB, sensor dicing)
- Occurred again in 2018 on one station equipped with p-in-n sensor!
- Cause is not clear, certainly related to sensor type (charge building)

Outline

IV trends

Temperature between -10 and -5 C



Unfortunately large surface current already at the beginning, not easy to interpolate with predictions based on Non Ionising Energy Loss scaling