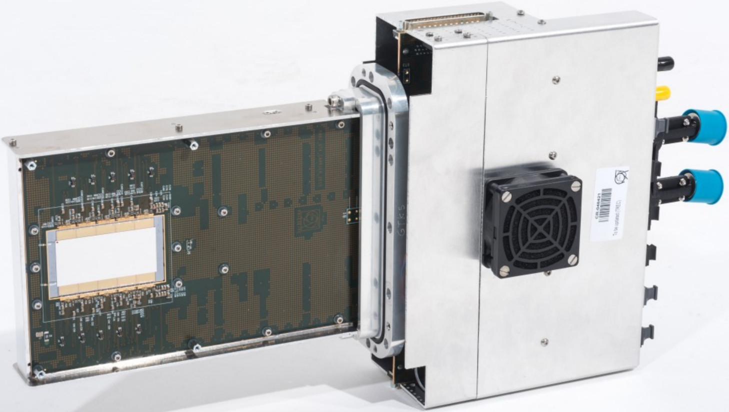
The NA62 GigaTracker

CERN EP-ESE Electronics Seminars

Mathieu PERRIN-TERRIN on behalf of the GTK Group

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



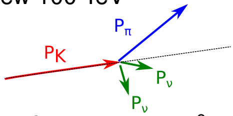
Outline

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

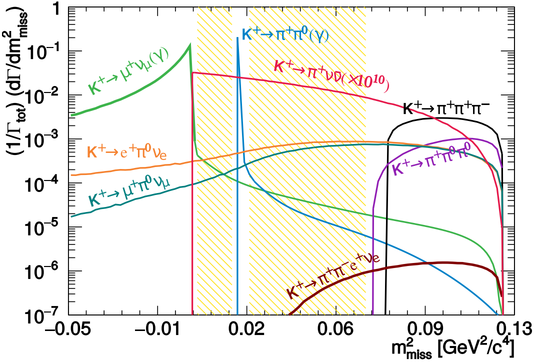
Full description of the detector in [JINST 14 (2019), p. P07010., arXiv:1904.12837]

The NA62 Experiment: measure $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ with 10% precision

- Probe **New Physics** at energy scales as high as few 100 TeV
- Experimentally **challenging**:
  - 2 neutrinos in the final state
  - $\mathcal{B} = (8.4 \pm 1.0) \times 10^{-11}$ in SM



- **Kinematics** very important to control background, $m^2_{miss} = |p_K - p_\pi|^2$
- Previous dedicated experiments (BNL) used **stopped beam**



The NA62 Experiment [JINST 12.5 (2017), P05025]

Decay in flight technique at CERN-SPS

- Continuous beam 750 MHz (6% K^+, 24% p, 70% π^+) at 75 GeV/c
- Beam being **not bunched**, all detectors must provide **timing** information
- As K do not decay at rest, $\vec{p}_K$ has to be measured to compute m^2_{miss}:

A (time resolved) **beam spectrometer** is needed: the GigaTracker (GTK)

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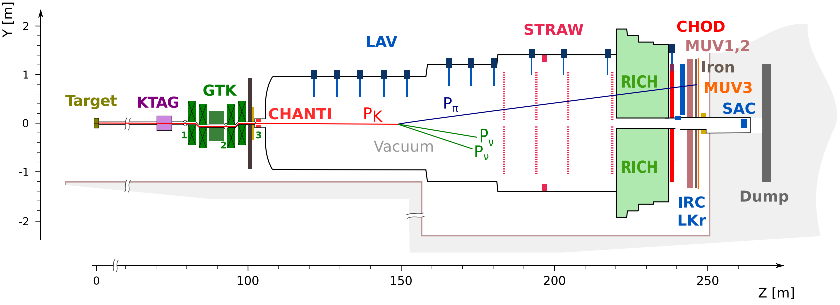

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Outline

The GigaTracker (GTK)

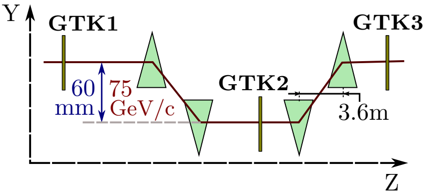
Beam Spectrometer

- Measures momentum, angle and time coordinate of **all beam particles**
- Sustains high **particle flux**
- Minimizes **material** budget

Beam Rate	750 MHz
Peak Flux	2.0 $\mathrm{MHz/mm^2}$
Peak Radiation	4.5×10^{14} $\mathrm{1MeV\ n_{eq.}/cm^2}$ 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

Design

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



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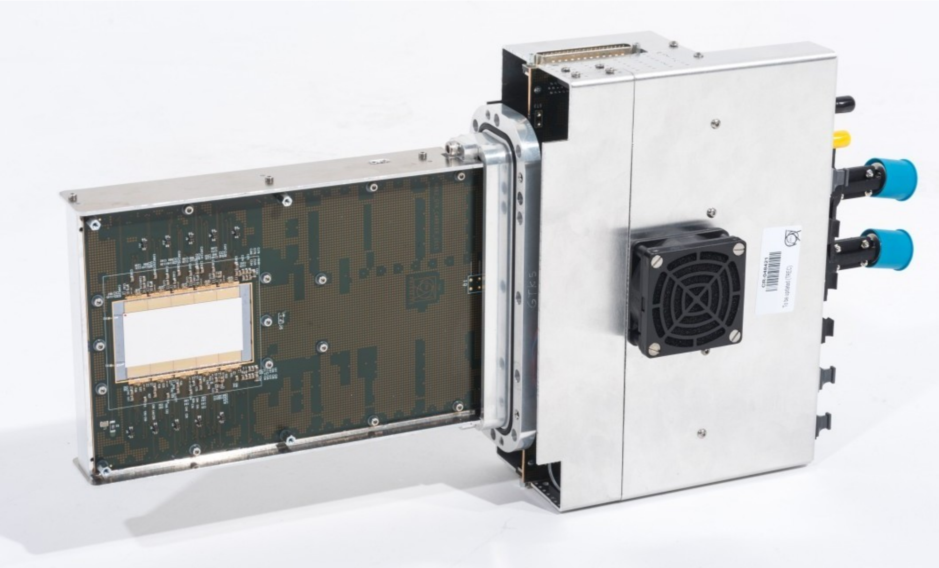

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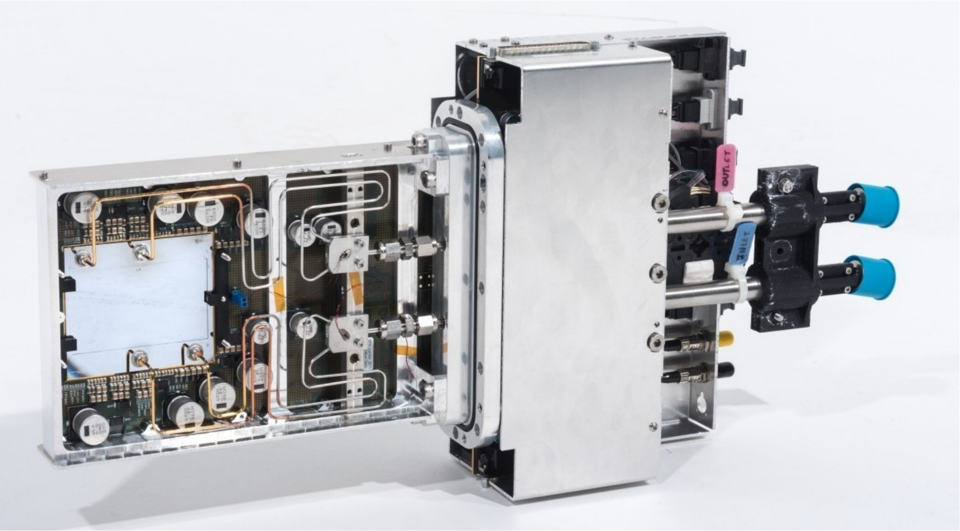

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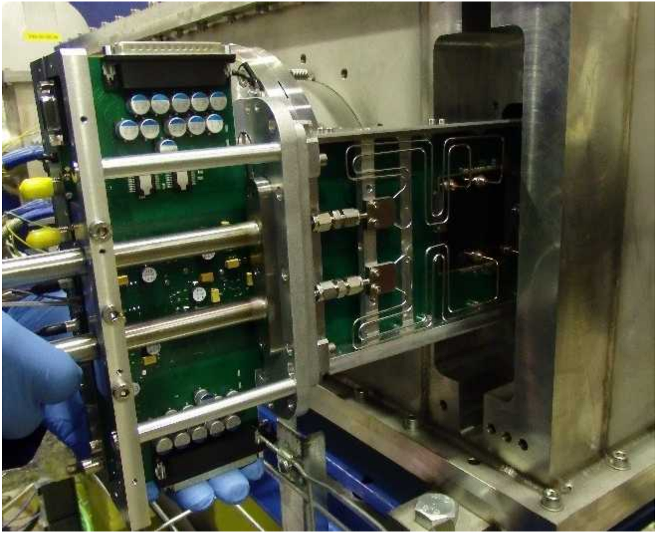
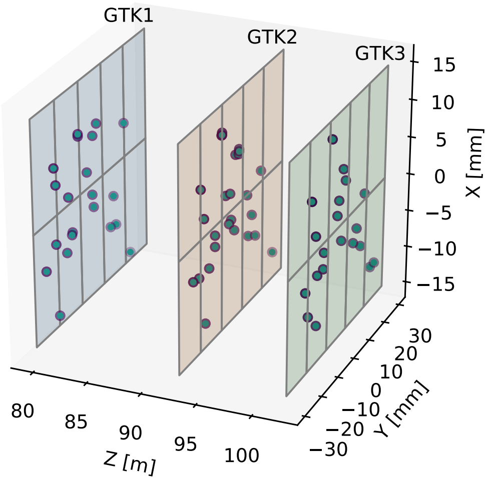


The need of timing

- **Association with other detectors** based on time-stamps
- Minimise material: only three tracking planes despite large occupancy
- Tracking in GTK relies on hit time-stamp (**4D Tracking**)



Typical Event at 35% beam intensity

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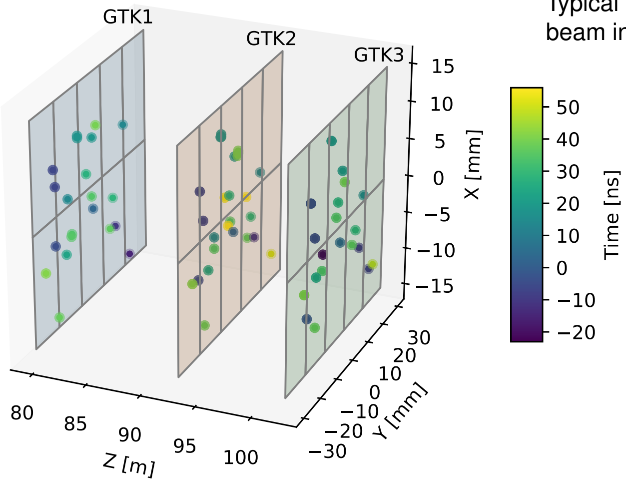

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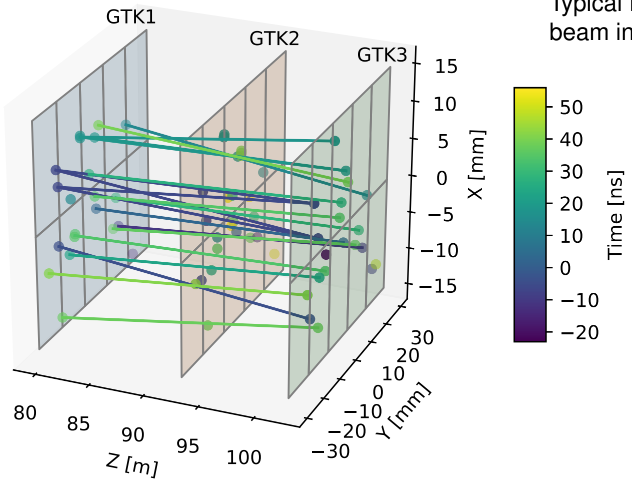
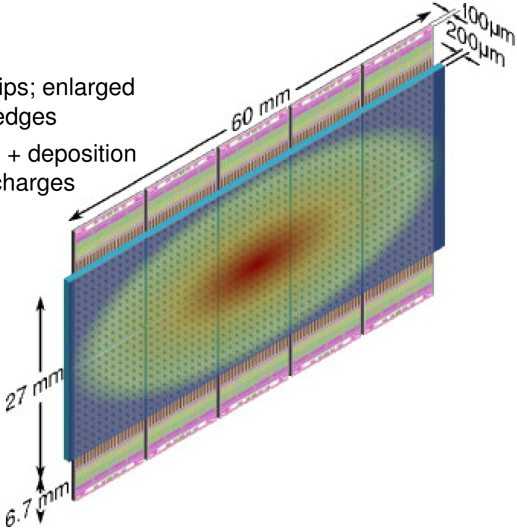


The Pixel Matrix

Hybrid Pixels

- 18'000 pixels of 300 $\times$ 300 μm^2
- Single **sensor** bonded to 10 chips; enlarged (400 $\times$ 300 μm^2) pixels at chip edges
- **Bump-Bonding**: Sn-Ag bumps + deposition of 2 $\times$ 3μm of BCB to avoid discharges
- **Sensor Type**: n-in-p and p-in-n



A Material Budget of 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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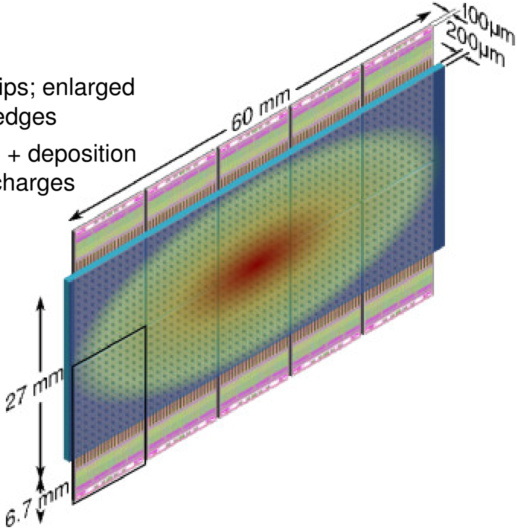

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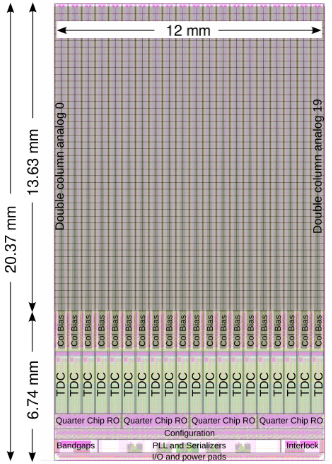
The TDCPix ASIC



Specifications

Time Resol	$< 200\,\mathrm{ps}$
TDC bin	97 ps
Peaking Time	$5\,\mathrm{ns}$
Peak Dose	$15\,\mathrm{MRad/y}$
Max Pixel Hit Rate	$180\,\mathrm{kHz}$
Chip Max. Hit Rate	$212\,\mathrm{MHz}, 130\,\mathrm{MHz/cm^2}$
Data Ouput Rate	$12.8\,\mathrm{Gb/s}$
Power	$4.1\,\mathrm{W}$
	$4.8\,\mathrm{W/cm^2}$ in EoC
	$0.32\,\mathrm{W/cm^2}$ in Px Array
Dynamic Range	$0.6 - 10\,\mathrm{fC}$
Efficiency	$> 99\%$

Architecture

- IBM 130nm CMOS technology

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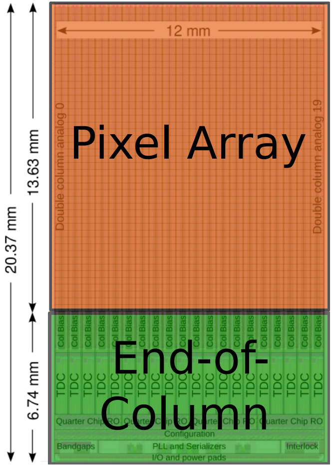

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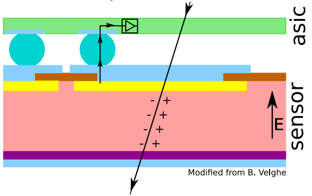
Architecture

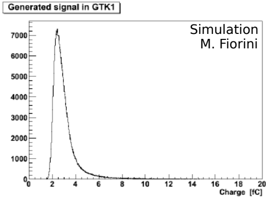
- IBM 130nm CMOS technology
- Digital logic fit in EoC to reduce digital switching noise in pixel array

Pixel Array

Signal Shaping

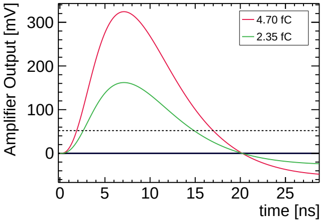
- **Pre-amplifier** (65 mV/fC, peak time: 5 ns) & **Discriminator** (5 bit DAC trim threshold)





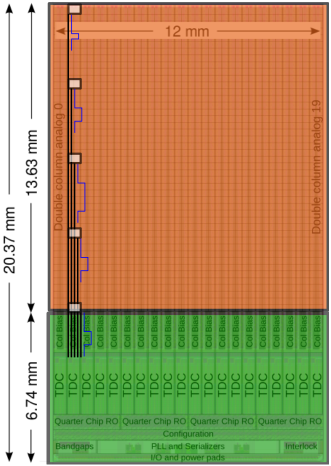
How to reach 200 ps time resolution?

- Sensor **over-depleted** (100-750 V bias) for fast charge collection (4-2 ns)
- **Charge release** is stochastic: Landau with Most Prob. Value at 2.4fC
- **Time-walk** up to 2.2 ns, depends on amplitude: record ToT for TW corrections



End-Of-Columns: Timing

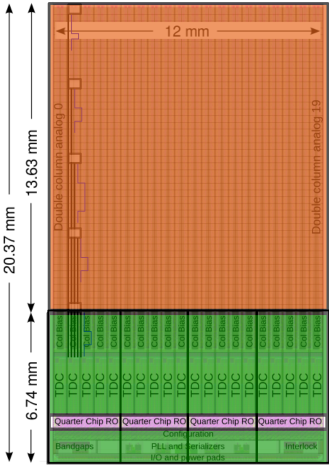
Time-stamping of rising and falling **edges** performed at the end-of-columns



- SEU protected by **triplicating digital logics**
- **Digital Signal** from pixels are multiplexed (5:1) in 360 time-stamping units
- Collision reduced by grouping non adjacent pixels
- Timing unit locked by first hit and addresses of pile-up hits encoded in hit word
- Time-stamps composed of fine & coarse counters (97 ps & 3.125ns) ranging up to 6.4 μs

End-Of-Columns: Output data

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



- **Hit words** are 48 bit long and contain:
  - hit address
  - pile-up hit address
  - leading coarse and fine time
  - ToT coarse and fine time
- Architecture is **Self triggered**
- All hit are sent out at 12.8 Gb/s with four **serialisers**
- **Frame words** are inserted every 6.4 μs to extend time-stamp up to 1718 s

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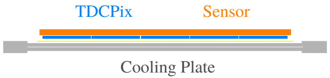

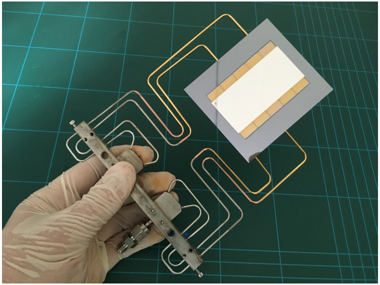

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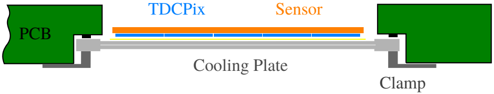

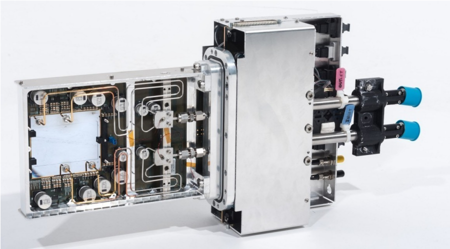

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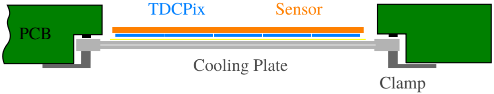

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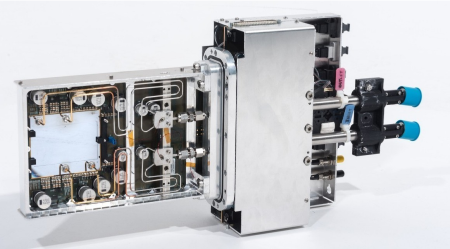

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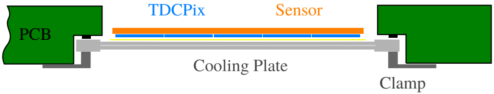
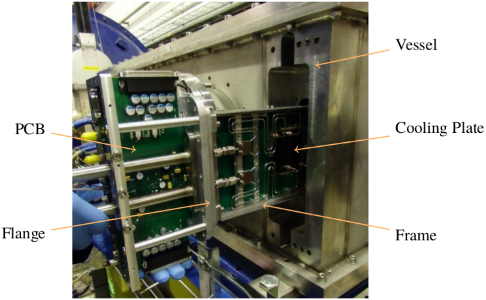
- **Cooling Plate** is clamped onto **PCB** (isostatic)
- **PCB** is mounted into frame and glued in **flange**
- **Flange** closes the **vacuum vessel**
- **Fast** mounting/dismounting for **station replacements**

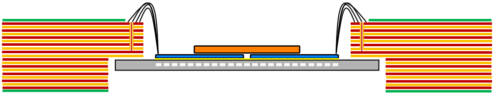


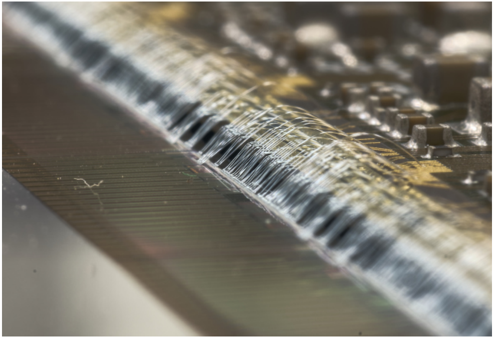


Electrical Integration

Wire Bonding

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



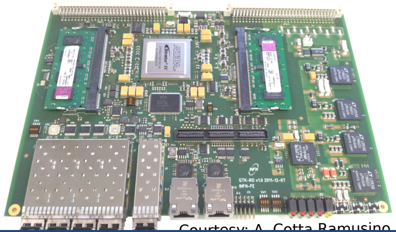


PCB

- 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 $200\,\mathrm{m}$ long fibers to the detector
- Triggers and clock received on **daugther card**
- **Trigger matching** logic implemented with **FPGA** Altera Stratix IV 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

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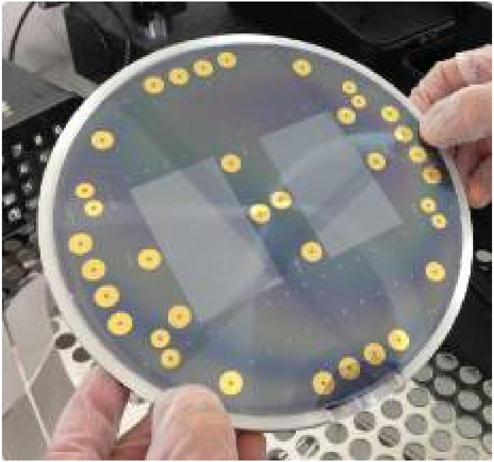
Micro-channel cooling matches the constraints

- 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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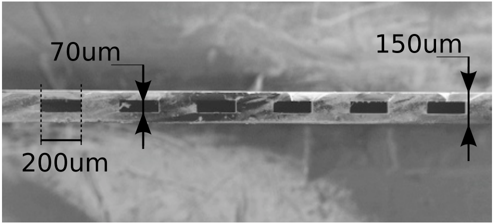

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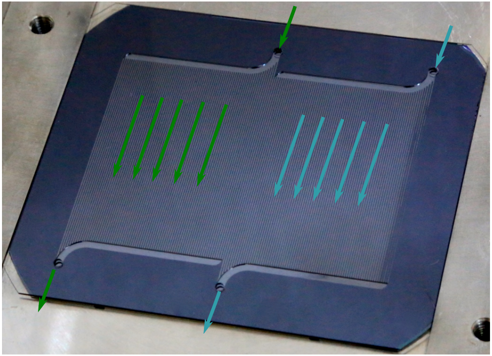

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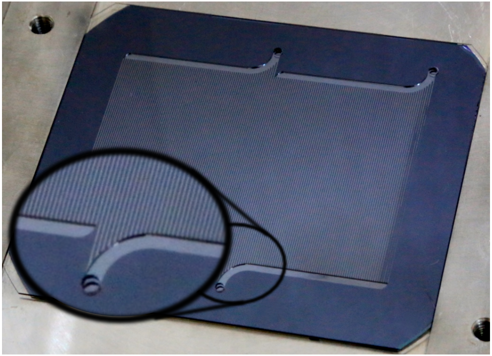
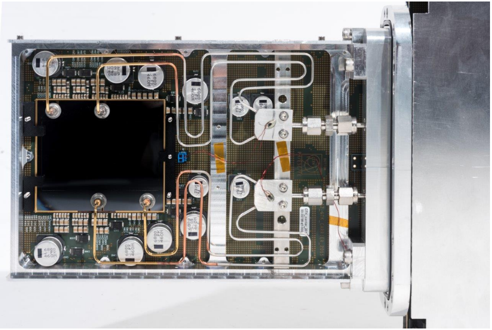


Cooling Plates

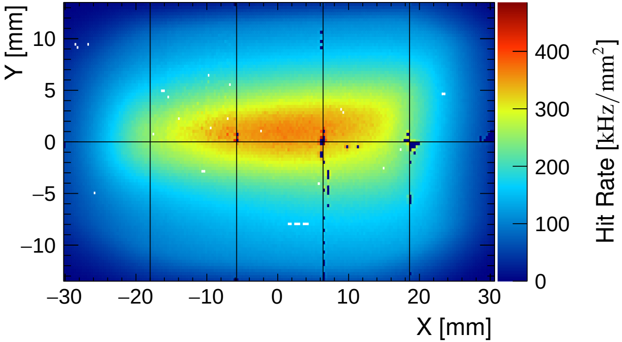
- Fabricated by **CEA Leti**
- **200μm$\times$ 70μm channels**
- Two cooling **circuits**
- Fluid brought in with **capillaries**
- Kovar **connectors** soldered onto cooling plate



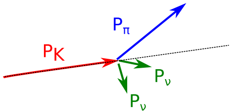
Outline

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)

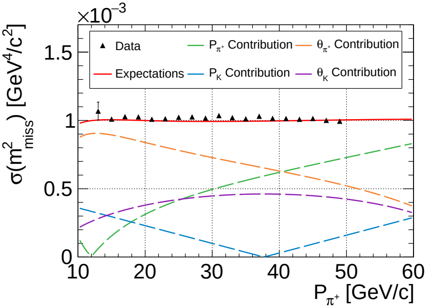


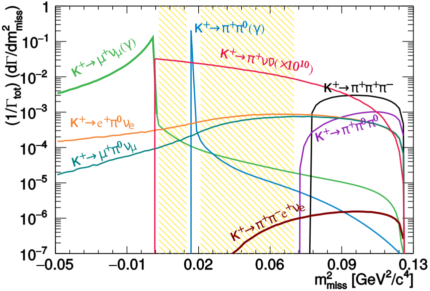
Kinematics



Kinematics

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

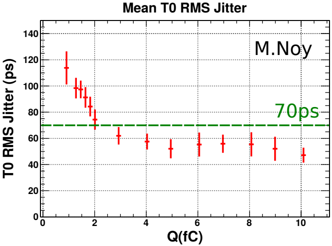




Early results with TDCPix Demonstrator (p-in-n sensor)

Charge Injection

- Infra-red **laser** pulse shone at pixel centre
- Sensor bias: 300V
- Time resolution: **70 ps** RMS for charged injected equivalent to MIP



J. Instrum. 6 (2011) C01086

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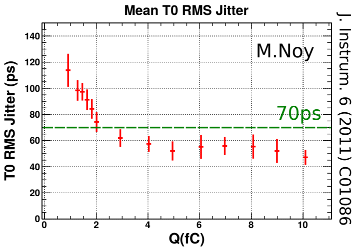
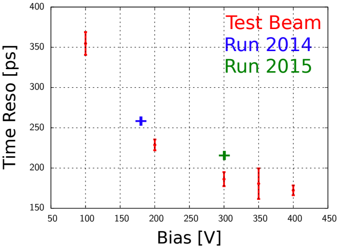


Beam Test

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



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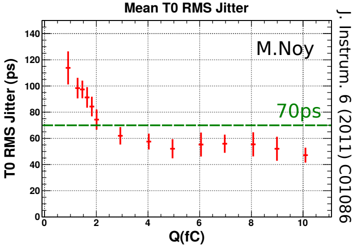

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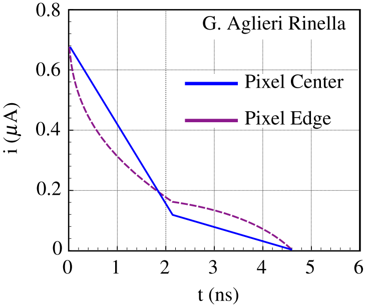
Difference Beam/Laser

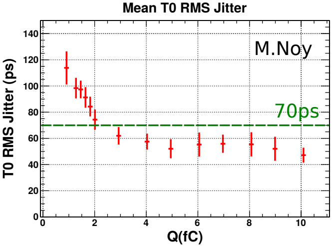
- Weighting field and charge straggling
- Time resol. as function of hit position (Laser, Demonstrator)



Early results with TDCPix Demonstrator (p-in-n sensor)

Charge Injection

- Infra-red **laser** pulse shone at pixel centre
- Sensor bias: 300V
- Time resolution: **70 ps** RMS for charged injected equivalent to MIP



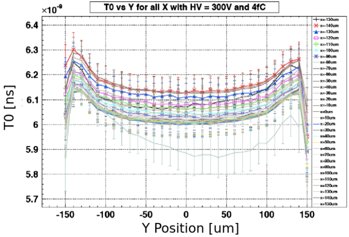
J. Instrum. 6 (2011) C01086

Beam Test

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

Difference Beam/Laser

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



Nucl. Inst. A 718 (2013)

Time resolution breakdown

Testing the **TDCPix Demonstrator** with laser and beam, the contributions to the time resolution are:

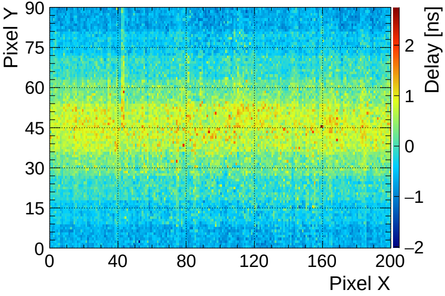
- 75 ps from the **chip**
- 85 ps from **weighting field** variation at pixel edge
- 60 ps **charge straggling**

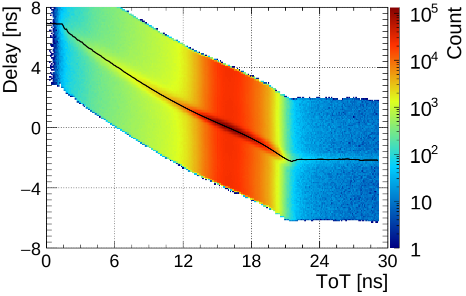
Eventually, the GigaTracker showed much better performances...

Time Resolution GigaTracker – Time Calibration

Time 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

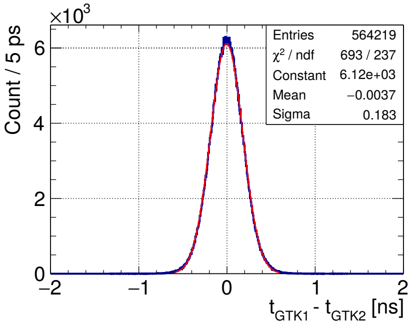
- **At detector installation** in 2016
- Sensor Type: **n-in-p**
- Operation **bias:** 100 V

Two Measurement Methods

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

Results

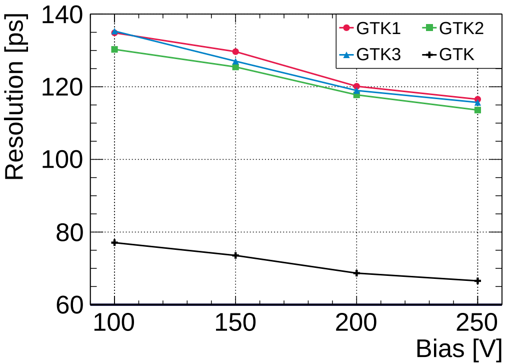
- **Hit resolution:** 130 ps
- **Track resolution:** 75 ps
- Design resolution matched



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 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

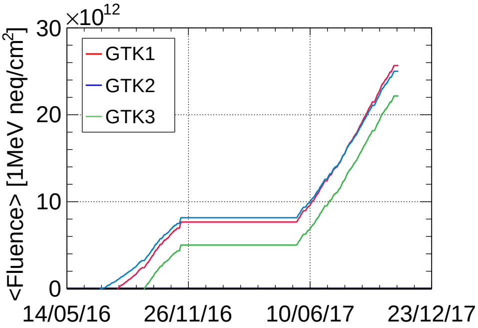
Stability over 2016 and 2017

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

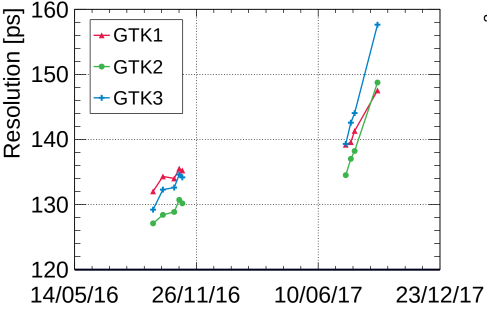
Irradiation

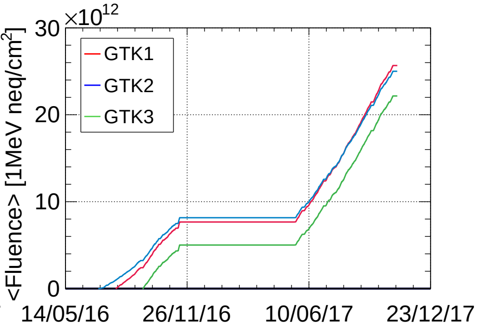
- Average Integrated **Fluence**: $2.5 \times 10^{13}\ \mathrm{1\,MeV\ eq.\ n/cm^2}$
- **Peak Fluence** 5 times higher ($1.25 \times 10^{14}\ \mathrm{1\,MeV\ eq.\ n/cm^2}$)



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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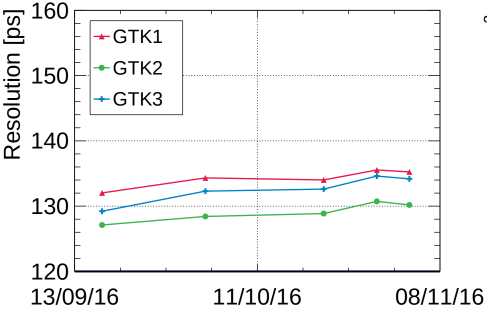

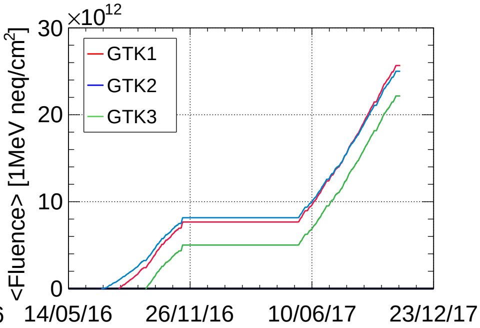

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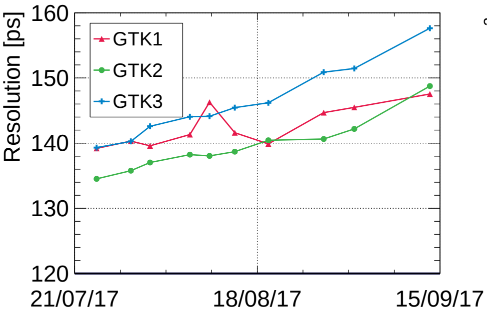
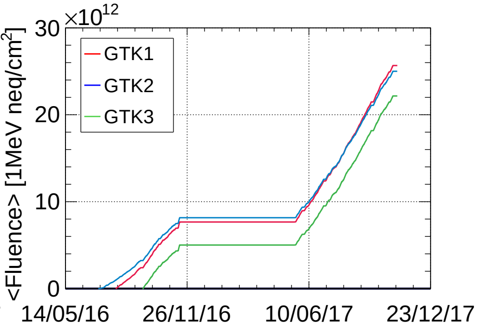
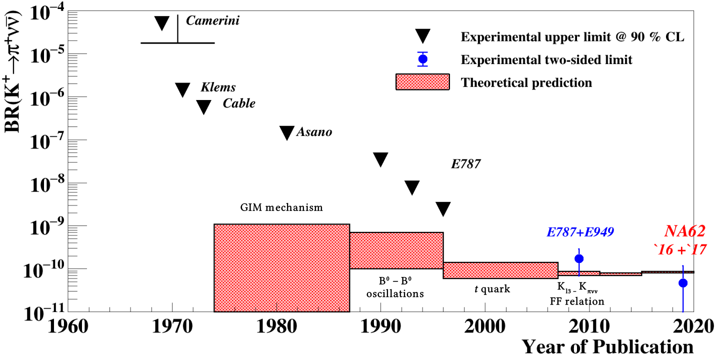




NA62 Physics Results for $K^+ \to \pi^+ \nu \bar{\nu}$

2016 and 2017 NA62 data analysed

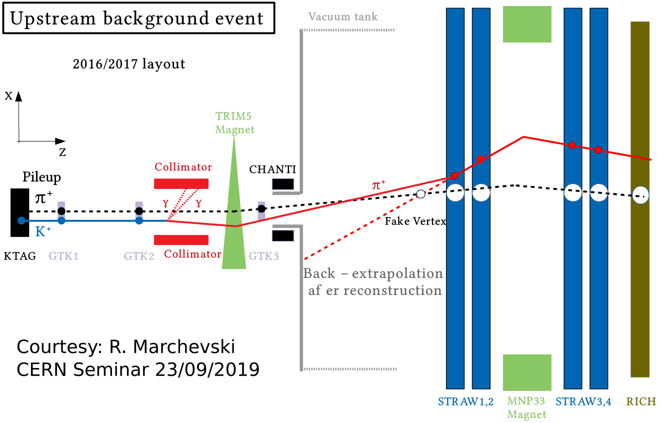
- For **2016** analysis, see [Phys. Lett. B 791, 156 (2019)]
- For **2017** analysis, see CERN seminar and press release:
  2 evts observed (expected: 2.16 ± 0.29 SM Signal and 1.5 ± 0.28 Bkg)
- 2016+2017 puts very **strong constraints on new physics**



Developments for 2021

A fourth station for NA62

- Upstream K decays generate background events
- 4th station will reduce mis-association between up and downstream tracks



Courtesy: R. Marchevski
CERN Seminar 23/09/2019

Outline

Conclusions

Summary

- The GigaTracker is the NA62 **4D beam tracker** and is essential to measure $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$
- First **physics results** validate the experiment design and strongly constrain new physics
- 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 for the first time

Prospects

- NA62 is preparing to run **after LS2** with an additional GTK station
- GTK **production** keeps going
- More studies needed to better understand time resolution

Extra Slides

5 Efficiency

6 Noise

7 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

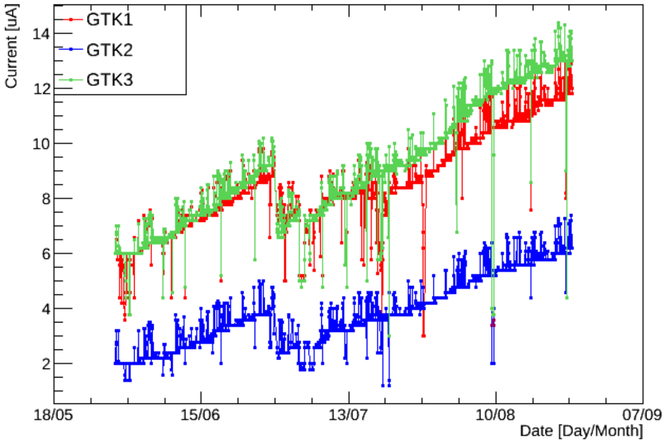
Noisy Pixels

- 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 build up)

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