ATLAS ITk Pixel quad module test beam measurements

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MAX-PLANCK-INSTITUT FÜR PHYSIK

ATLAS EXPERIMENT

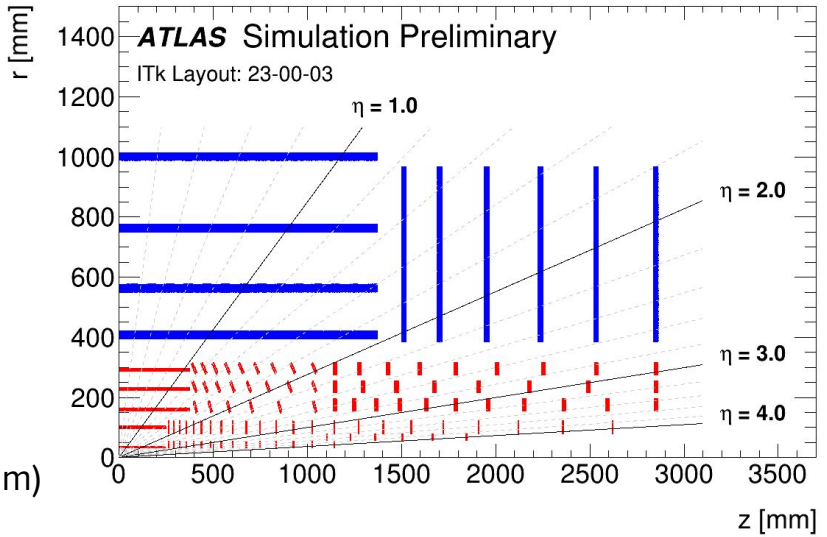
Upgrade of the ATLAS experiment

The High-Luminosity LHC (HL-LHC)

- data taking from **2030**
- challenging environment due to increased:
  - instantaneous luminosity (~ $7.5 \cdot 10^{34}$ $cm^{-2}s^{-1}$)
  - pile-up events per bunch crossing (~ 200 events/bunch crossing)
  - radiation damage (TID up to 10 MGy)
- upgrade of all detector systems of the ATLAS Experiment

The current Inner Detector will be replaced with the **Inner Tracker (ITk)** consisting of silicon **strip** and **pixel** modules.

A schematic depiction of the ITk Layout



ATL-PHYS-PUB-2021-024

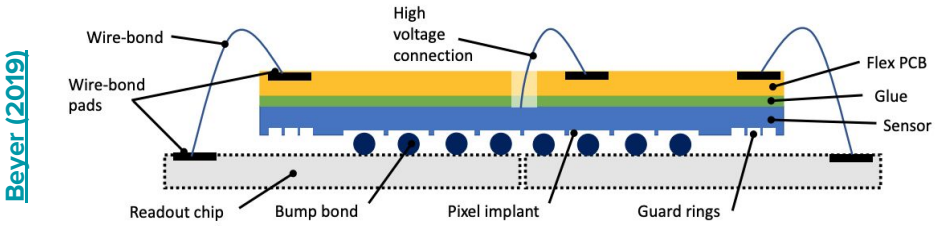
The ITk Pixel detector will include:

- single-chip 3D sensors in L0 (r = 34 mm)
  - 2x2 cm^2 size;
- four-chip (quad) planar sensors in L1-L4 (r = 99 - 291 mm)
  - 4x4 cm^2 size.

ATLAS ITk pixel modules assembly and testing

The ITk pixel modules are assembled in two steps:

- **bump bonding**, where readout chips are attached to the sensor → bare module;
- **module assembly**, where the flex PCB (hybrid) is glued to the bare module



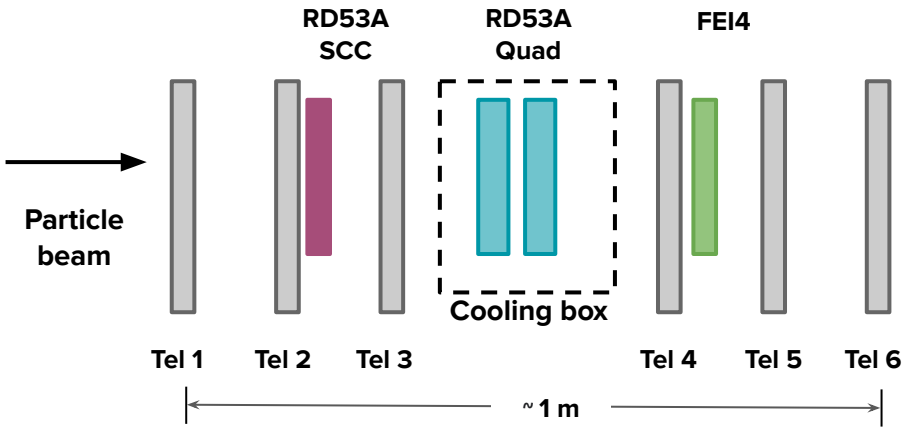
Beyer (2019)

The performance of assembled modules is evaluated in laboratory and **test-beam** measurements.

Module testing setup at MPP

Experimental setup

- The test-beam measurements are performed at CERN SPS in the North Area
  - Beam of pions with E = **120.0 GeV**
- Scintillators in coincidence are used for triggering purposes
- **EUDAQ1** framework is used for the data acquisition



Beam telescope
RD53A single-chip card (SCC) as a timing reference
FEI4 single-chip card
RD53A quad modules with n-in-p planar sensors of 150 µm thickness and 50x50 µm^2 pixel size:

- non-irradiated Hamamatsu (HPK) Q8
- non-irradiated Micron Q2
  - PT biasing structure
- irradiated HPK Q4
  - Fluence: ϕ_{eq} = 5 x 10^{15} n$_{eq}$cm^{-2}

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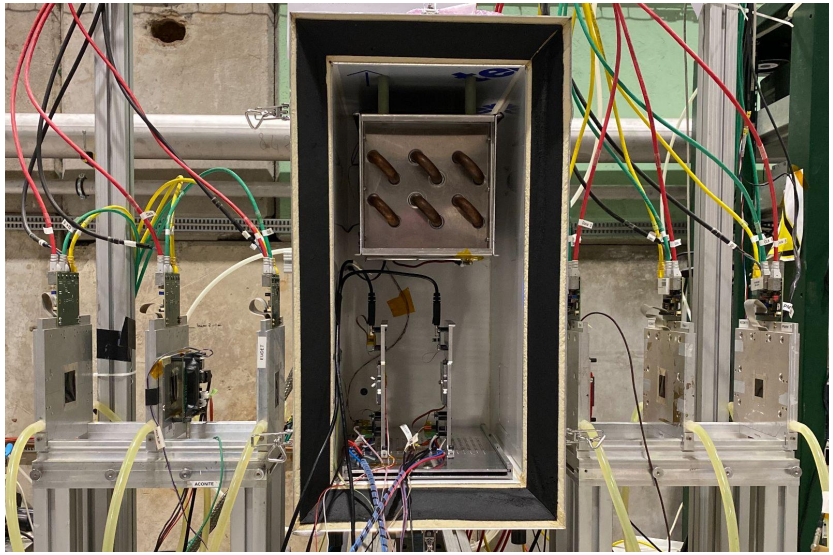
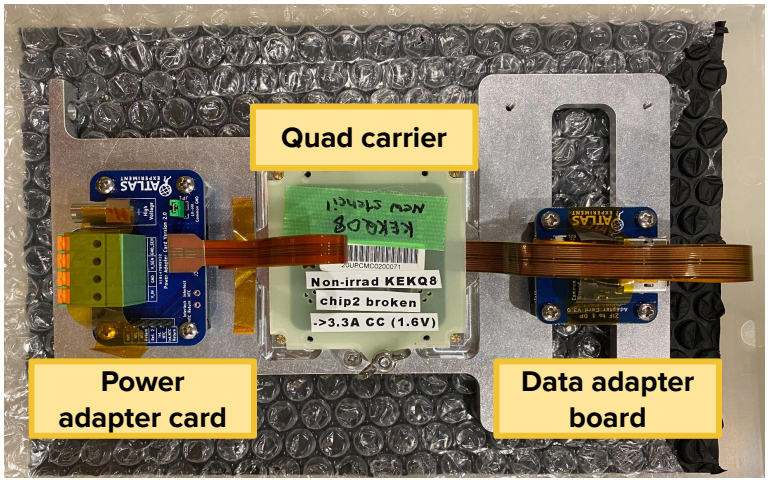


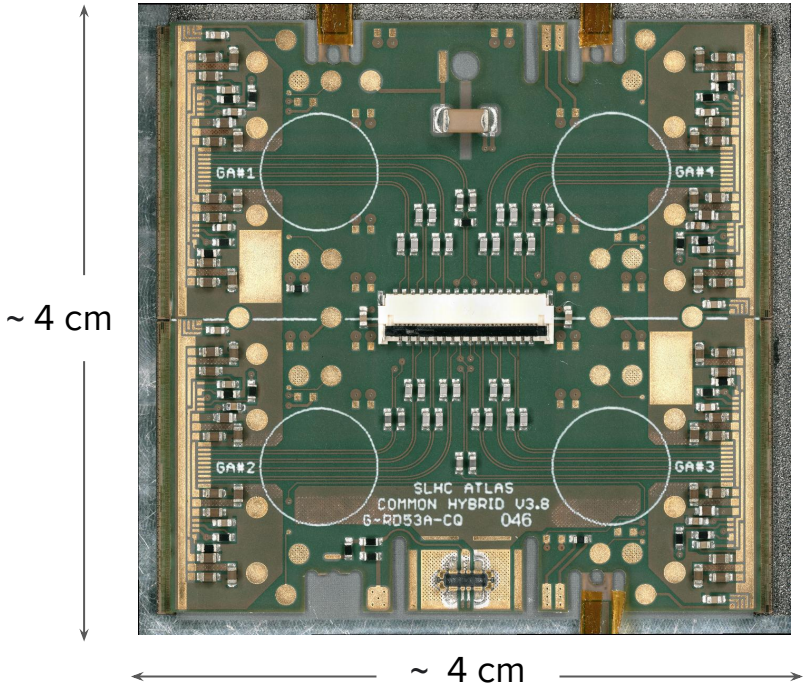
Frame with mounted RD53A quad module



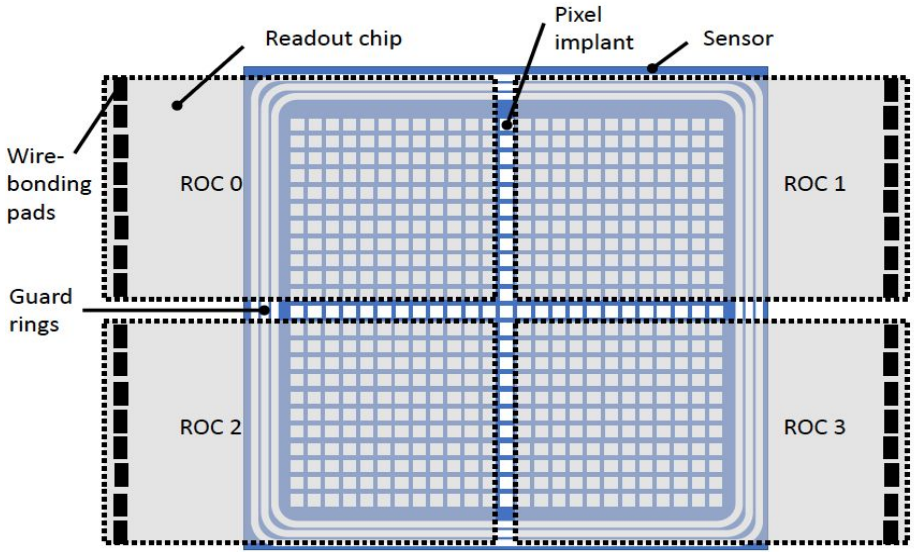
- To be able to scan different chips, the position of the module with respect to the beam is changed.

ATLAS ITk RD53A quad modules

Example of the assembled RD53A module

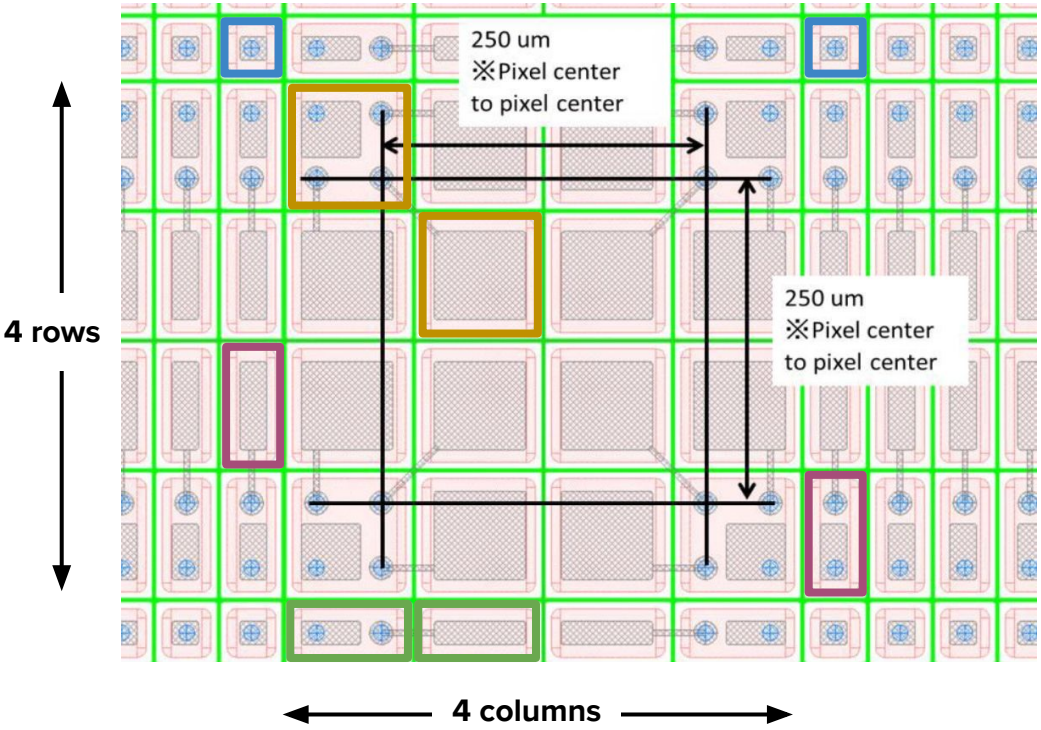


Sketch of quad-module layout



Inter-chip region

- The gap between the four chips bump bonded to the quad sensor
  - Four central columns and rows of the sensor
  - Different pixel sizes to cover this area



Pixel size (column × row; column=X, row=Y)

- 50×50 μm^2
- 100×100 μm^2
- 50×100 μm^2
- 100×50 μm^2

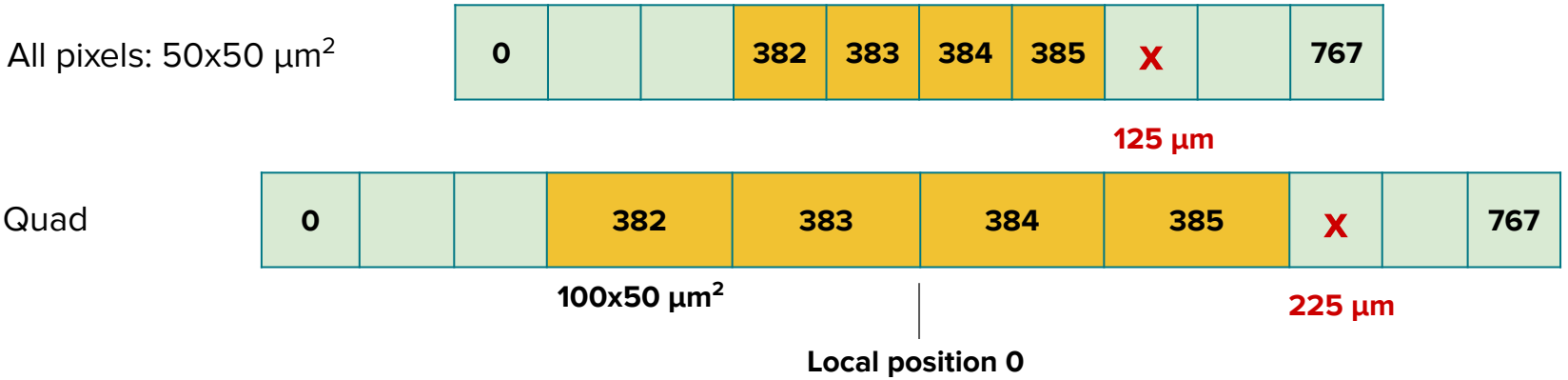
Data reconstruction

- The raw data contain basic pixel hit information: column, row, ToT, LV1 ID
  - Hits close in space are grouped into clusters
  - Column and row of the cluster center can be converted to the hit position

} In the data reconstruction and analysis software

- The **Corryvreckan** framework is used for the data reconstruction and analysis
  - In this framework the sensor is expected to have a uniform pixel matrix.

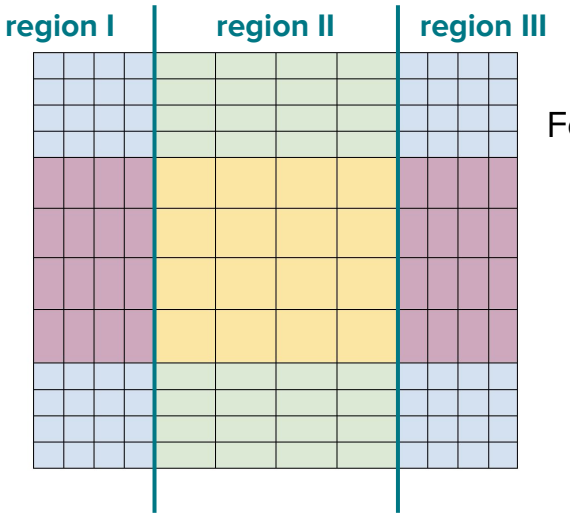
Example: The hit cluster center has column ID: 386



Pixel number refers to the center of the pixel

New Corryvreckan geometry class

- The new - **ITkPixQuad** - class implemented
  - A detector with this inter-chip region configuration is created by specifying coordinates in the detector configuration file as: **`coordinates = "cartesian_itkpixquad"`**
  - The pixel size in each direction depends on the region on the quad



Following functions were modified according to the quad geometry:

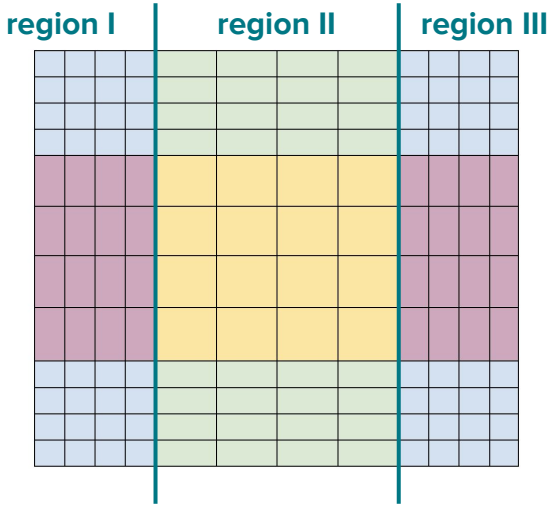
- Calculation of the local position based on the column and row;
- Determination of the row and column from the local position;
- Calculation of the size of the detector;
- Calculation of the in-pixel position from column/row and local position;
- Calculation of the spatial resolution based on the column/row of the pixel.

New Corryvreckan analysis module

- **Previous experience:** test-beam analysis when testing only single-chip cards performed using AnalysisDUT and AnalysisEfficiency modules
  - Both modules would have to be modified to study the quad module and inter-chip region

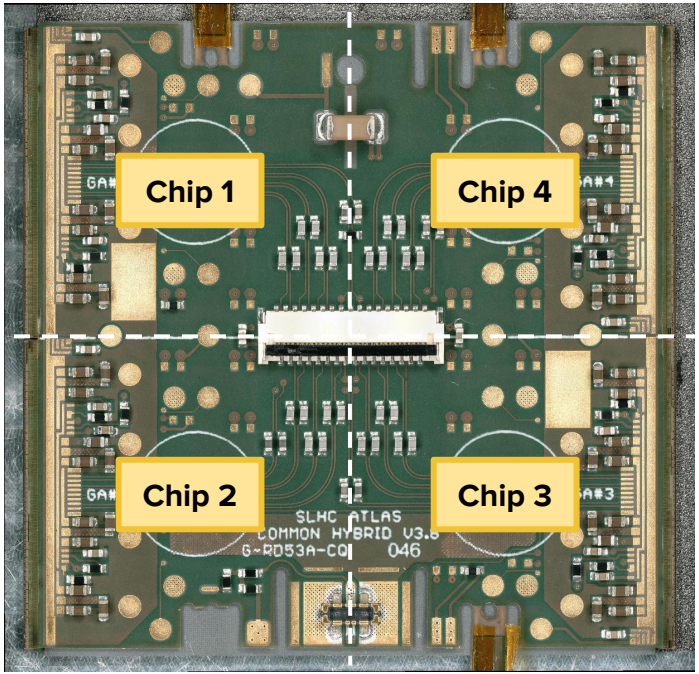
- The new - **AnalysisITkPixQuad** - module created, which can be used to determine:
  - Cluster size distribution in X and Y;
  - Residual distribution in X and Y;
  - Hit efficiency.

  All quantities can be determined separately for:
  - 50x50 μm^2 size pixels;
  - the inter-chip region.



RD53A Quad module layout

- Readout system: record hits per chip
- EUDAQ converter: combine data from four chips into one detector plane
- Corryvreckan framework: read data per detector plane



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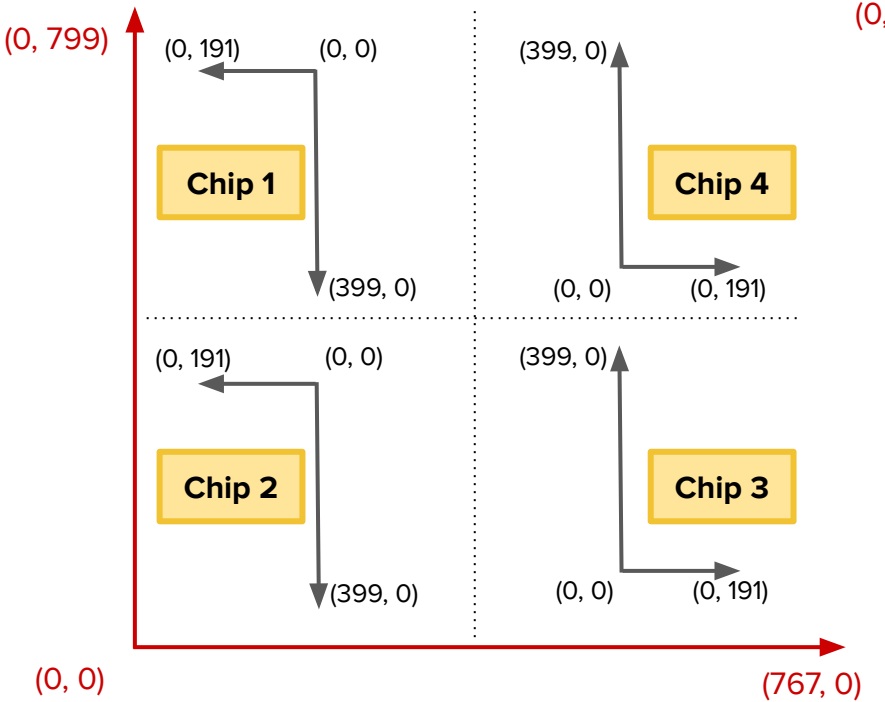
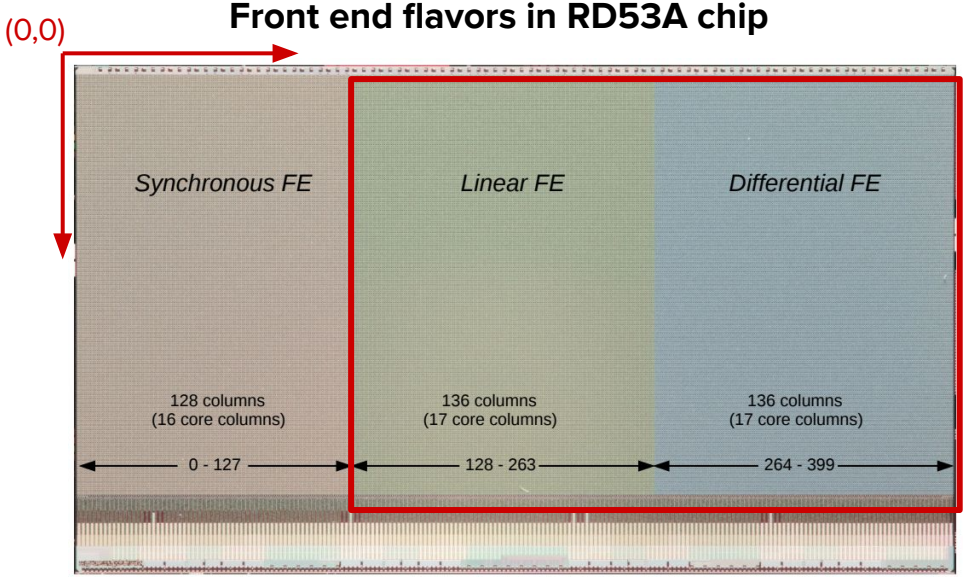
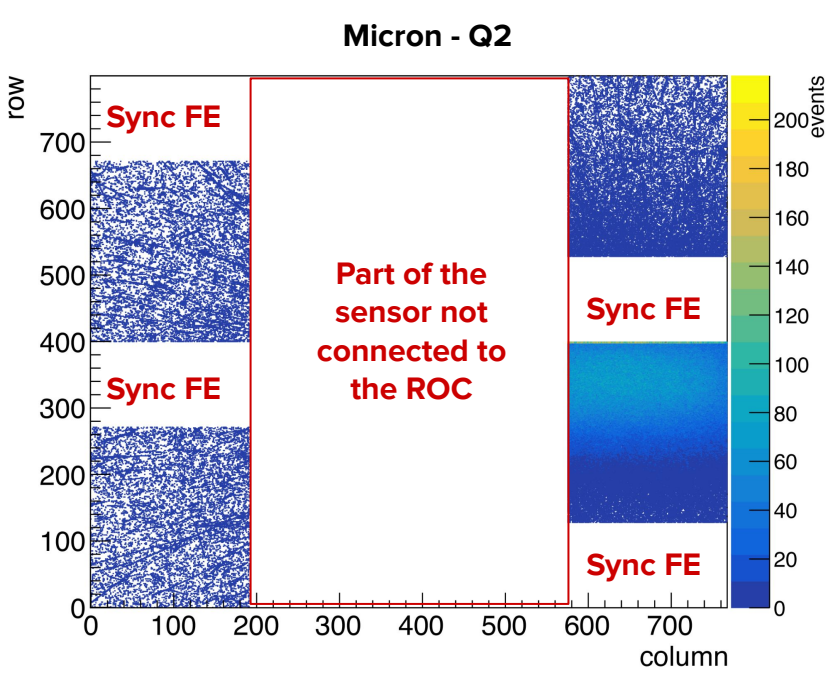


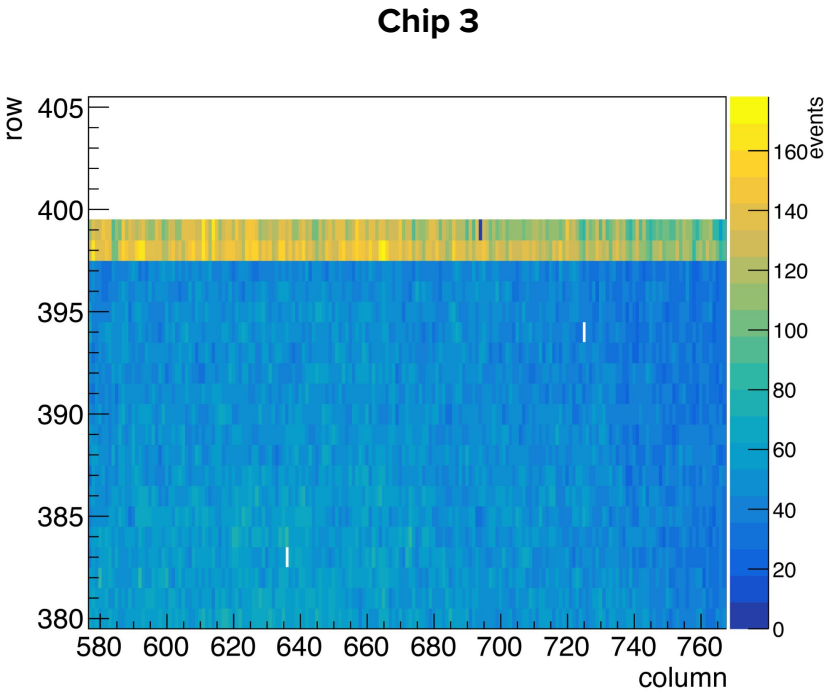
Front end flavors in RD53A chip



- RD53A chip is half the size of the final chip
- Synchronous FE is not used in data taking

Hit map example





- Module positioned such that the beam is focused on chip 3

Row **398 and 399:** 50x100 µm^2 pixels - twice as many hits compared to other pixels

Hit efficiency measurement

- **Track selection**
  - Only tracks with a hit on the reference DUT (timing reference) within LV1 limits are considered for the analysis

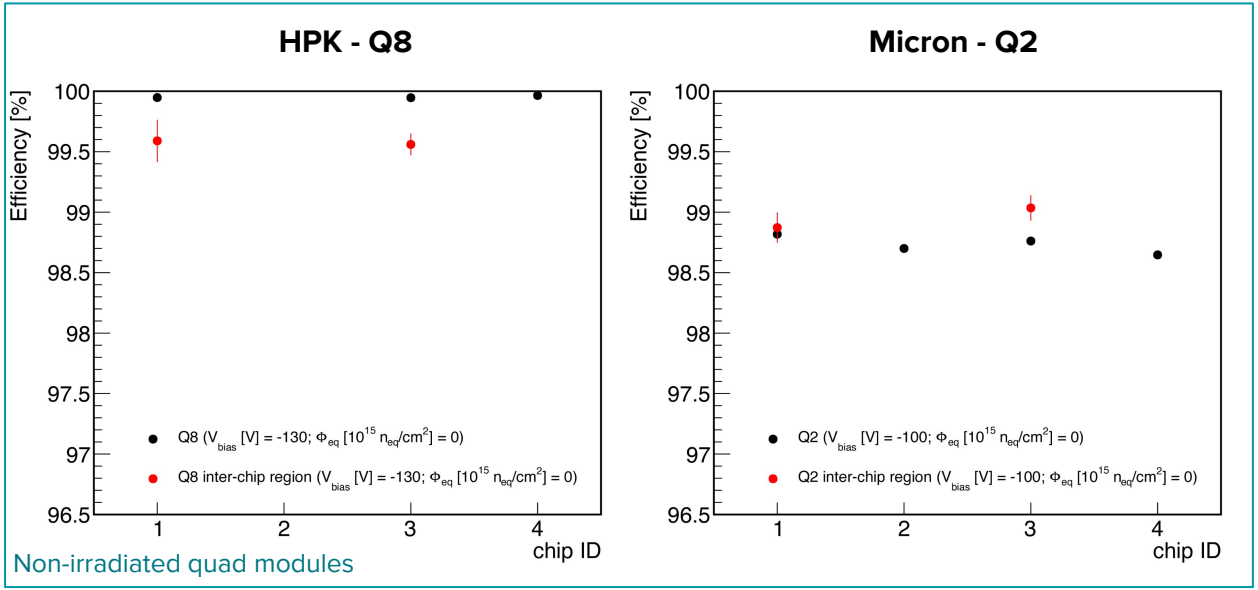
- **DUT cluster association**
  - Clusters on quad modules are assigned to the reconstructed tracks if they are within twice the pixel pitch in both directions

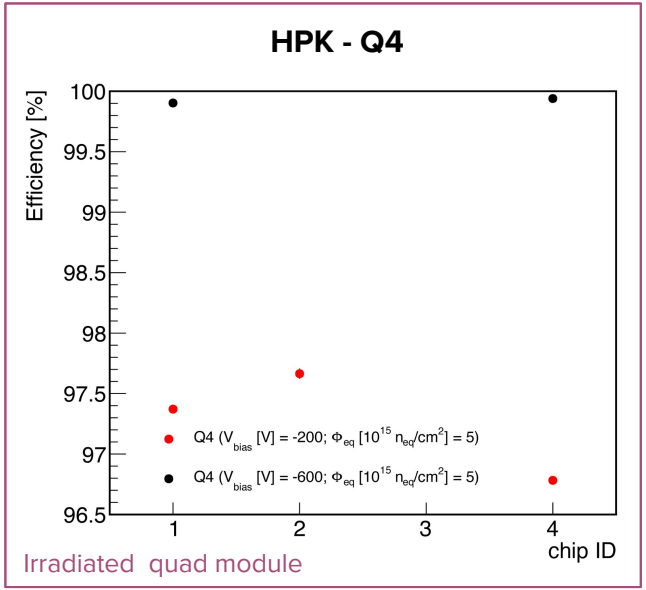
- **Hit efficiency**

$$\varepsilon = \frac{\text{number of tracks with an assigned cluster on the DUT}}{\text{total number of tracks intersecting the DUT}}$$

DUT - Device Under Test

Hit efficiency per chip





HPK - Q8

- Chip 2 was disabled
- ε> **99.9%** for all 3 measured chips
- ε> **99.5% (inter-chip region)**

Micron - Q2

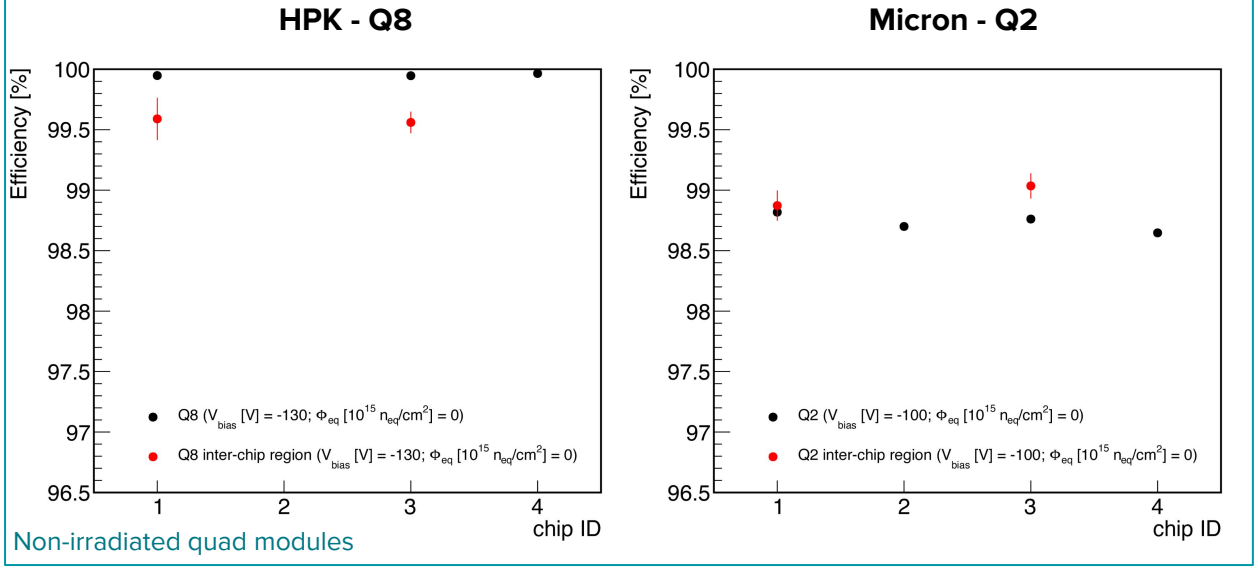
- All chips enabled
- ε > **98.5%**

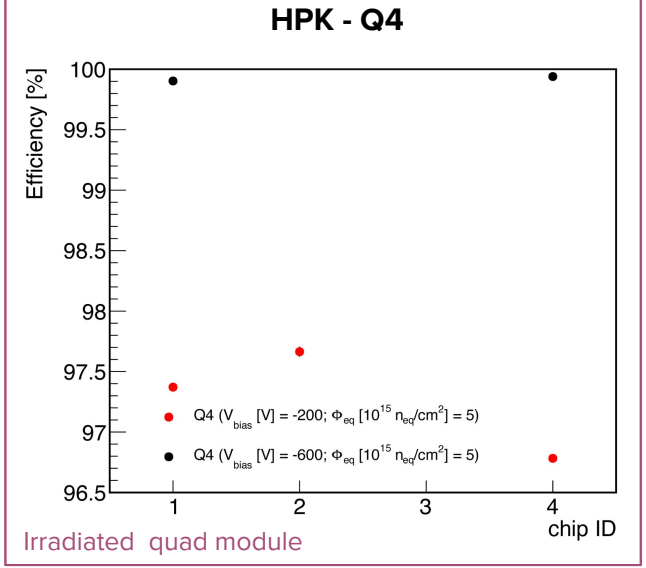
HPK - Q4

- Chip 3 was disabled
- ε ~ **97.0%** (-200 V)
- ε ~ **99.9%** (-600 V)

The efficiency uncertainties are statistical.

Hit efficiency per chip





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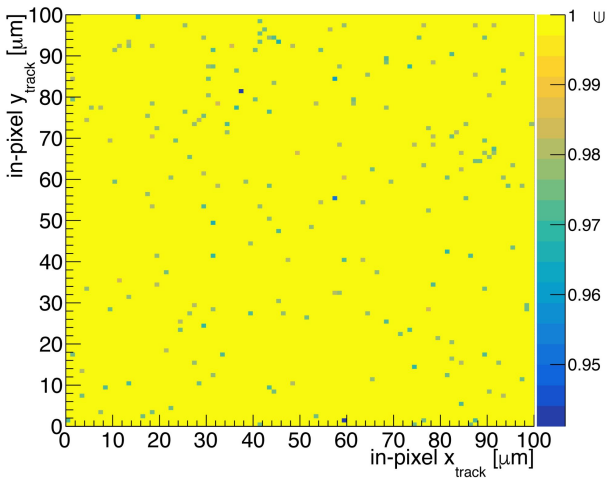
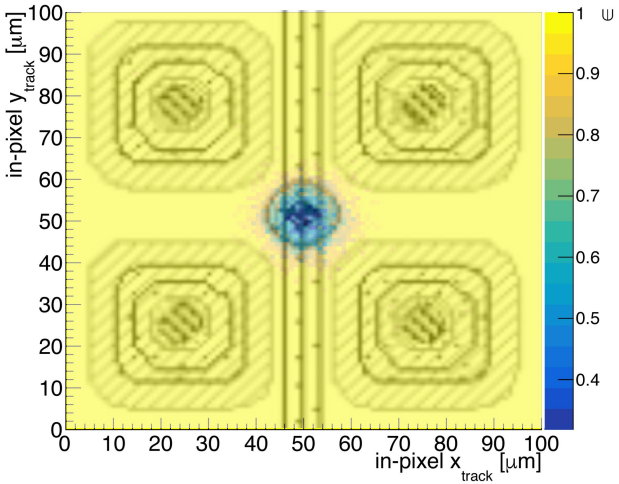
ITk requirements for planar sensors: **Non-irradiated modules > 98%;** **Irradiated modules > 97%**

Hit efficiency map (50x50 µm² pixels)

HPK - Q8

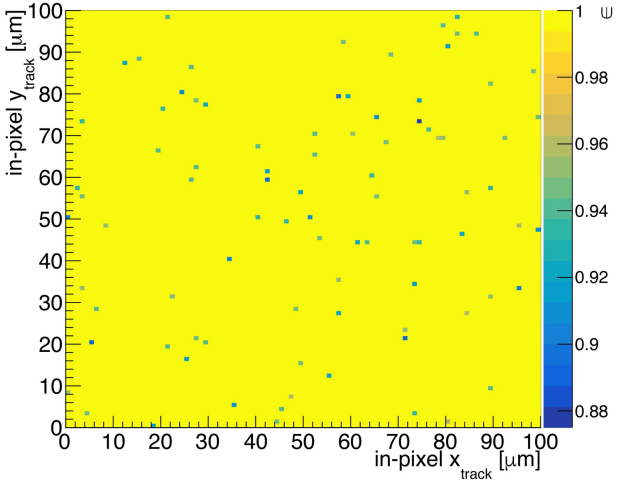


Micron - Q2



Non-irradiated quad modules

HPK - Q4



Irradiated quad module

Threshold tuning: 1500e
Bias voltage: -130 V
Leakage current: -0.2 µA
T: ~20 °C

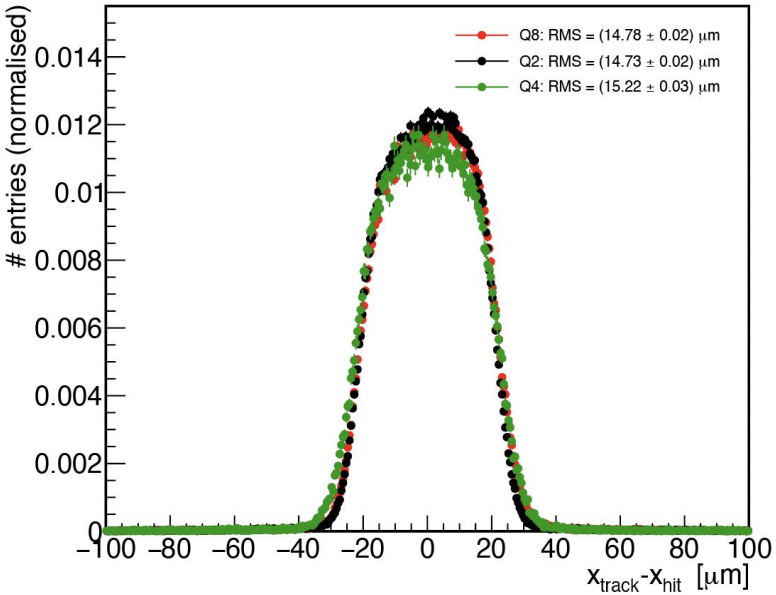
Threshold tuning: 1500e
Bias voltage: -100 V
Leakage current: -4.8 µA
T: ~25 °C

with a punch-through biasing structure

Threshold tuning: 1500e
Bias voltage: -600 V
Leakage current: -100 µA
T: ~ -30 °

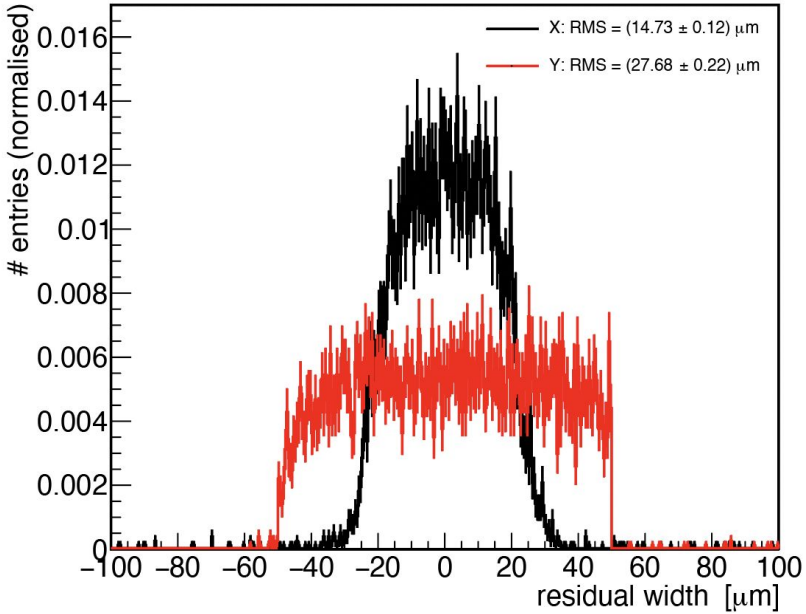
Residual distribution

50x50 µm² pixels: X dimension



Unbiased residuals $r^2 = \sigma^2_{int} + \sigma^2_{tel}$

Q8: inter-chip region



σ_{int} (50 µm, 100 µm) = 14.43 µm, 28.87 µm
σ_{tel} ~ 5 µm

Summary and outlook

- Three RD53A quad modules have been successfully measured during the test-beam campaigns in 2021
  - Two non-irradiated quad modules;
  - One irradiated quad module.

- The data is reconstructed and analysed using the Corryvreckan framework
  - The framework was further developed to allow the analysis of sensors with non-uniform matrices.

- The hit efficiencies of the modules fulfill the requirements for ITk planar sensors
  - Non-irradiated modules > 98%;
  - Irradiated modules > 97%.

- The functionality of the inter-chip region is verified
- The residual distributions for three measured quads are compatible with the expectation for respective pixel sizes.

- More studies will be performed with ITkPix v1.1 modules.