Performance of thin n-on-p planar pixel sensors for the ATLAS ITK

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Introduction

• ATLAS detector upgrade for **High Luminosity phase (HL-LHC)** $\Rightarrow \mathcal{L}_{\text{instantaneous}} = 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

• Inner detector replaced with new **all silicon Inner Tracker** (pixels + strips).

• **ITK requirements** for silicon pixel detectors include:
  
  ➢ **Higher granularity** $\Rightarrow$ Smaller pitch pixels of $50 \times 50 \mu\text{m}^2$ or $25 \times 100 \mu\text{m}^2$.
  
  ➢ **Radiation hardness** $\Rightarrow$ up to $3 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ for planar sensors.
  
  ➢ **Hit efficiency** $>$ 97% for HL-LHC (at Max 600V)
Setup

• Sensors are produced by FBK and assembled at IZM with the RD53a front-end on a single chip card.

• Presented modules were **Irradiated at CERN PS** Irrad facility.

• Modules were measured **before and after irradiation in a testbeam setup** at CERN (120 GeV pions) and DESY (5 GeV electrons).

• Data acquisition setup include Mimosa telescope planes, scintillators for external trigger, Bdaq53 readout, cooling chamber for controlled temperatures at -50 °C.

• Tracks **reconstruction using Eutelescope** and data is **analyzed using Tbmon2** software.

• All modules were tuned before measurement to achieve lowest possible threshold (~1000e).
Modules overview

- RD53 n-in-p planar sensors are produced on 6” wafer by FBK.

Measured modules details:

- **100-25-noPT**
  - thickness: 100μm
  - cell: 25x100μm²
  - No biasing dot
  - Not Irradiated

- **130-25-noPT**
  - thickness: 130μm
  - cell: 25x100μm²
  - No biasing dot
  - Irradiated at CERN PS

- **130-50-PT**
  - thickness: 130μm
  - cell: 50x50μm²
  - With biasing dot
  - Irradiated at CERN PS
Results

Non-Irradiated modules
Hit efficiency vs. bias voltage

- 25x100μm² pixel module with 100μm thick sensor, Non-irradiated.

- Tuned threshold:
  - Linear = 1060e
  - Differential = 1160e

- Depletion voltage for the sensor is $V_{\text{depletion}} = 20\text{V}$.

- Hit efficiency for Linear & Differential FE show similar results.
Results

Irradiated modules
Module irradiation

- Irradiation at CERN PS Irrad facility $\rightarrow$ Inhomogeneous profile + irradiation beam misalignment.

- Fluence map is reconstructed from Beam Profile Monitor (BMP) with the dosimetry results measured on the foil sheet mounted behind the modules.

- Fluence analysis estimates $\sim$20% uncertainty from measurements and fitting.

Differential

Linear

Synchronous

Avg fluence

Avg fluence

Avg fluence

\[ \text{Avg fluence} = \begin{cases} \text{5.4e15} & \text{for Synchronous} \\ \text{3.5e15} & \text{for Linear} \\ \text{1.3e15} & \text{for Differential} \end{cases} \]

\[ n_{eq}/cm^2 \]

\[ n_{eq}/cm^2 \]

\[ n_{eq}/cm^2 \]

\([0-127] \]

\([128-263] \]

\([264-399] \]
Tuning

• Tuning for RD53a chip is performed using the Bdaq53. Scanning processes is performed for each front-end flavor independently.

• Example of threshold distribution for a 25x100μm² irradiated module after tuning.
Analysis regions

- In the testbeam setup the sensors were centered on the particle beam to cover two front-ends at the same time.

- Hit efficiency map at 500V measured at CERN testbeam setup.

- Each front-end was analyzed separately using TBmon2.
In-pixel efficiency maps

Hit efficiency is defined as the fraction of reconstructed tracks crossing a module that have an associated hit in that module.

- 2x2 Pixel efficiency map shows the overall hit efficiency of the module.
- At 500V the hit efficiency is $95.29 \pm 0.16\%$.
- Significant hit efficiency loss is visible in the biasing structure region.
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- At 500V the hit efficiency is $95.29 \pm 0.16\%$.
- Significant hit efficiency loss is visible in the biasing structure region.
In-pixel efficiency maps

- 2x2 Pixel efficiency maps for a module with 25x100μm² cell size and no Biasing structure. Sensor design is overlaid on the pixel map.

- At 500V the hit efficiency is $98.3\pm0.4\%$.

- At 500V pixel efficiency map shows uniform efficiency due to the no biasing structure sensor design.
In-pixel efficiency maps

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- At 500V pixel efficiency map shows uniform efficiency due to the no biasing structure sensor design.
Hit efficiency: Fiducial region

- Studying the influence of biasing structure on the hit efficiency → comparing the hit efficiency of the full pixel geometry with the core pixel.

- Analysis restricted to **Linear FE**.

- Over all hit efficiency **increases by ~3%** in the fiducial region.
Hit efficiency vs. bias voltage: Threshold effect

- Overall hit efficiency for 50x50μm² pixel module.

- Hit efficiency vs. bias voltage measured for Linear front-end.

- Tuned threshold:
  - 1400e⁻ (measured at CERN October 2018)
  - 1180e⁻ (measured at DESY December 2018)

- For lower tuned threshold value:
  - 15% Higher hit efficiency at 200V
  - Earlier saturation of hit efficiency at 400V

**Graph**

- Linear FE
  - $\Phi = 3.5 \times 10^{15} \text{n}_{eq}/\text{cm}^2$

- Measurements:
  - 130μm 50x50μm²
  - Threshold=1400e⁻ [CERN]
  - Threshold=1180e⁻ [DESY]
Hit efficiency vs. bias voltage

- Hit efficiency for an irradiated 25x100μm² pixel module.

- Average fluence on:
  - Differential FE $\Phi = 1.3 \times 10^{15} n_{eq}/cm^2$
  - Linear FE $\Phi = 3.5 \times 10^{15} n_{eq}/cm^2$

- Similar tuned threshold value for both front ends of 1300e

- Hit efficiency saturation at 200V for $\Phi = 1.3 \times 10^{15} n_{eq}/$

- Hit efficiency saturation at 500V for $\Phi = 3.5 \times 10^{15} n_{eq}/cm^2$

Threshold = 1300e

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Cluster size and cross talk

- Irradiated 25x100μm² module. Analysis region restricted to linear FE.

- From previous studies cross talk appears for all front ends.
  - Natalia Emriskova, RD53
  - Review Open Session
  - https://indico.cern.ch/event/769894/contributions/3229980/attachments/1765304/2865819/AFE_REVIEW_CERN_test_results.pdf

- Analysis of cluster size shows probability of cluster size >1 between neighboring pixels.
Cluster size and cross talk

- No indication of cross talk from studying the cluster size.

More statistics required
Conclusions

• At 500V, linear FE, $\Phi = 3.5 \times 10^{15} \text{n}_{eq}/\text{cm}^2$, threshold = 1400e with permanent biasing structure shows hit efficiency of $95.29 \pm 0.16\%$ while when excluding the biasing dot the hit efficiency increases to $98.4 \pm 0.1\%$.

• 25x100$\mu$m$^2$ sensor with threshold=1250e
  → Linear FE with $\Phi = 3.5 \times 10^{15} \text{n}_{eq}/\text{cm}^2$ → hit efficiency about 98%.
  → Differential FE with $\Phi = 1.3 \times 10^{15} \text{n}_{eq}/\text{cm}^2$ → hit efficiency about 99%.

• At 200V, irradiated module at $\Phi = 3.5 \times 10^{15} \text{n}_{eq}/\text{cm}^2$ (linear FE) shows hit efficiency of $94.22 \pm 0.69\%$ while with lower fluence of $\Phi = 1.3 \times 10^{15} \text{n}_{eq}/\text{cm}^2$ (diff FE) it shows 15% increase of efficiency of $98.7 \pm 0.4\%$.

• Testbeam data (at DESY) for 25x100$\mu$m$^2$ do not show indications of cross-talk → More data might be needed.
Outlook

- Waiting for 2 more modules to be assembled for testbeam measurements in May 2019.

- study the performance of non-irradiated front-end flavors with lowest achievable threshold for each flavor.

- An investigation on threshold homogeneity for RD53A for non-irradiated and irradiated modules is planned in March testbeam.

- Measurements of hit efficiency as a function of **fluence**. Irradiation planned at **Karlsruhe in 2019**:
  - $\Phi = 1 \times 10^{15} n_{eq}/cm^2$
  - $\Phi = 2 \times 10^{15} n_{eq}/cm^2$
  - $\Phi = 3 \times 10^{15} n_{eq}/cm^2$

- New production of planar sensors from **FBK** arriving in few months.
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