Thin and Edgeless silicon planar pixel sensors

For ATLAS inner tracker upgrade

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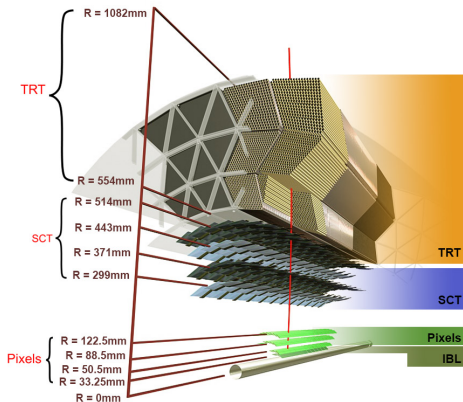4 Brookhaven National Laboratory, Instrumentation Division 535B, Upton, NY - USA

PSD - Detectors for high energy physics - September 7, 2017

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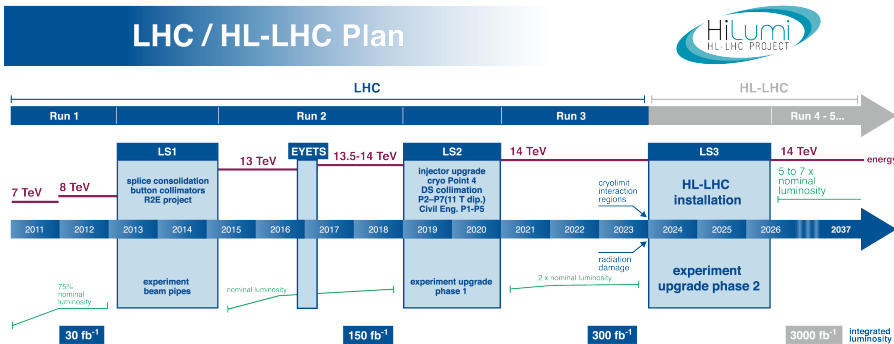
ATLAS Tracker

- ▶ 3 subdetectors: Pixels, SCT, TRT
- ▶ Pixel detectors composed of now 4 barrel layers (IBL)
- ▶ η acceptance: $-2.5 < \eta < 2.5$
- ▶ Excellent performances in terms of spatial resolution and hit efficiency, but
- ▶ Expected fluence at the end of lifetime: 1 and 5 $\times 10^{15} n_{eq}/cm^2$

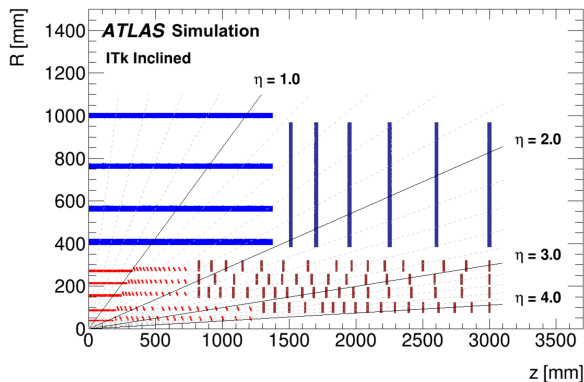$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

ATLAS Upgrade

ATLAS data taking phase in HL LHC conditions (start in 2026):

▶ Peak luminosity of $L_{inst} \simeq 7.5 \times 10^{34} cm^{-2} s^{-1}$

▶ 200 inelastic pp collisons per bunch crossing

▶ By the end of 2037, ATLAS will collect 3000 fb^{-1} (4000 fb^{-1}?)

▶ Fluence inner tracker $2 \times 10^{16} n_{eq}/cm^2$ (4 times IBL fluence)

ATLAS Inner Tracker Upgrade (ITK) Layout

pixels (red) - strips (blue)

Pixel options:

▶ 3D silicon pixels

▶ Planar silicon pixels

▶ CMOS pixels

Pixel TDR due for end of 2017:

    ∗ All silicon tracker

    ∗ 10 m^2 of pixels more than 600 Millions electronic channels

    ∗ 200 m^2 of strips

ITK Pixels Challenges

ITK major challenges:

▶ **Radiation hardness**: Retain a 97% efficiency with a fluence up to $2 \times 10^{16} n_{eq}/cm^2$ for innermost layer
  ∗ Thinner sensors to fight charge trapping
  ∗ Rad harder 3D sensors for innermost layer (cf Cinzia's talk)
  ∗ LPNHE 130 μm thick sensors irradiated at $1 \times 10^{16} n_{eq}/cm^2$, our R&D focuses on planar sensors for intermediate layers

▶ **High event rate and pile up compliance**:
  ∗ Granularity ($50\mu m \times 50\mu m$ or $25\mu m \times 100\mu m$ pitch instead of $250\mu m \times 50\mu m$)
  ∗ New chip RD53 $50 \times 50\mu m$ to deal with high data rate at HL-LHC

▶ **Increase the geometrical acceptance**
  ∗ Instrument at high eta, cf Inclined layout
  ∗ Reduction of dead area $\Rightarrow$ LPNHE Active edge sensors

LPNHE-FBK-INFN sensors

Active edge sensors
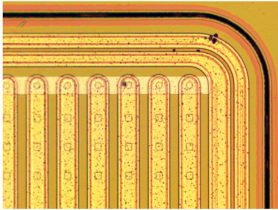
- ▶ N-on-P devices
- ▶ Pixel pitch: 50 μm by 250 μm *
- ▶ Temporary metal for biasing in initial sensor QA before bonding to FE
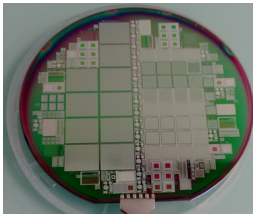
- ▶ Thickness: 200 μm

Active edge:

- ▶ Deep Reactive Ion Etching
- ▶ 100 μm from last pixel; 0, 2 GRs

Development of Edgeless n-on-p Planar Pixel Sensors for future ATLAS Upgrades, *M Bomben et al*, Nucl. Instr. and Meth. A 2013:712:41-47 ‗
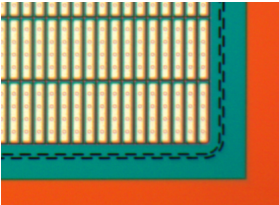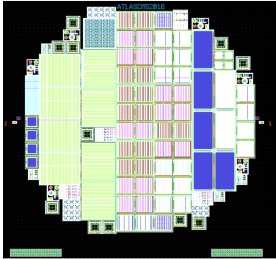
Thin sensors

- ▶ 6 inches SiSi wafers
- ▶ N-on-P devices
- ▶ Pixel pitch: 50 μm by 250 μm *
- ▶ Thickness: 100 and 130 μm

- ▶ Passivation against discharge: BCB
- ▶ 2 sensors irradiated up to a fluence of $1.1 \times 10^{16} n_{eq}/cm^2$

*Compatible with IBL read-out chip (FEI4)

Production 3: Thin and Active edge sensors

FBK production: 4 FEI4b sensors

- ▶ SiSi wafers
- ▶ N-on-P devices
- ▶ thickness: 100 μm
- ▶ 2 FEI4 50 μm pixel to trench, 0 GRs
- ▶ 1 FEI4 75 μm pixel to trench, 0 GRs
- ▶ 1 FEI4 75 μm pixel to trench, 1 GR
- ▶ Segmented trench design
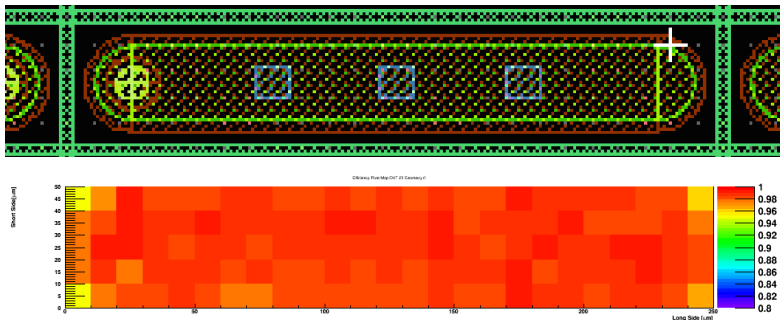
Also: 5 RD53 compatible sensors

Status: Bump bonding at IZM (Berlin)

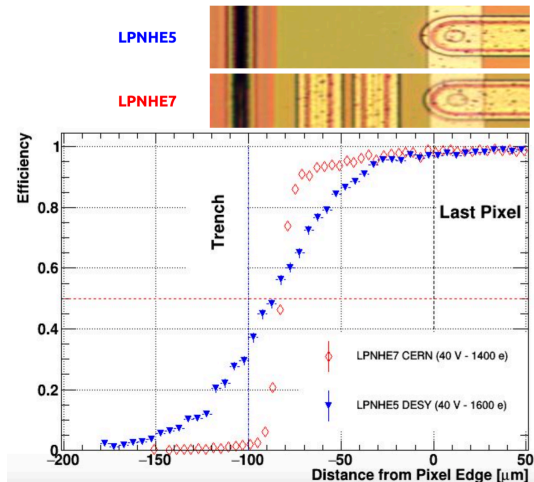# Testbeam results: Active edge sensors, not irradiated

Global Efficiency: 98 % when biased at 40 V (depleted at 20V)

In Pixel efficiency:

Temporary metal line to bias sensors before bump bonding:
No permanent bias structures results in **uniform hit efficiency**
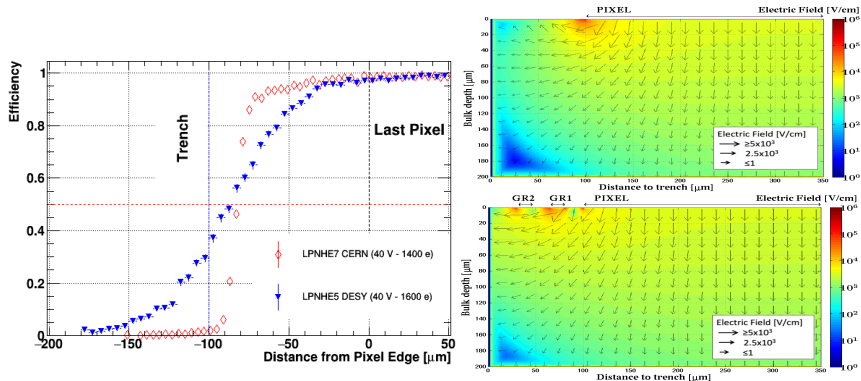
Edge Efficiency

LPNHE5

LPNHE7

LPNHE 5 (0 GR):
- ► Higher threshold 1600e
- ► Multiple scattering DESY

LPNHE 7 (2GR)

Efficiency higher than 50% **up to 92** μm **from the last pixel**
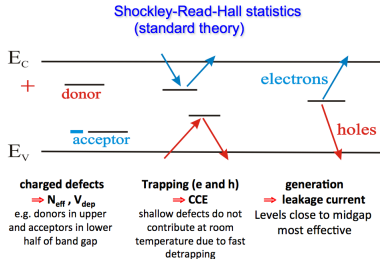
⇒ GRs don't impact too severely on the hit-efficiency

▶ **Charge is not collected and reemitted by GRs** apart from few μm below the GR area

▶ **Simulation TCAD** supports the hypothesis

▶ Uninstrumented area is no longer dead!

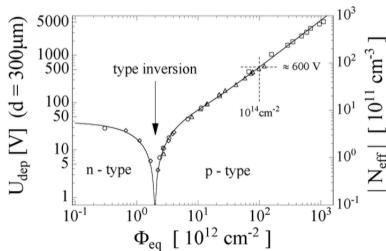# Testbeam results: Thin irradiated sensors

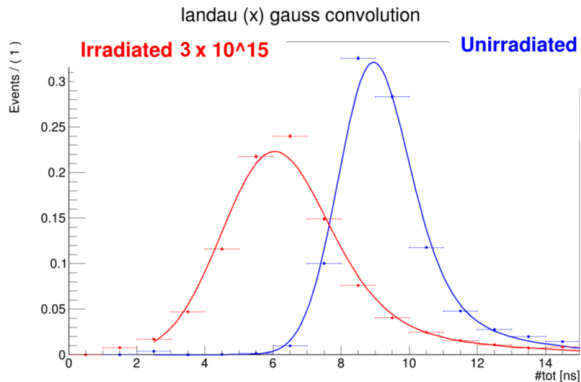Radiation (NIEL) creates new energy states (deep defects) in the gap:

- ▶ Charge trapping
- ▶ Type inversion

Macroscopic effects:

1. ↘ Charge Collection efficiency
2. ↗ Leakage Current
3. ↗ Depletion Voltage

Charge collection at $3 \times 10^{15} n_{eq}/cm^2$

landau (x) gauss convolution

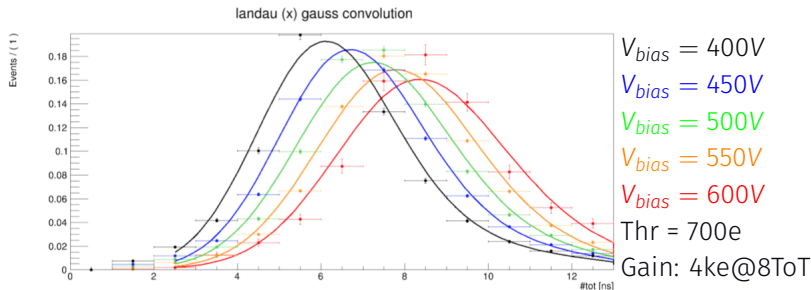**Irradiated 3 x 10^15**   **Unirradiated**

$V_{bias} = 600V$
$V_{bias} = 100V$
Thr = 1ke
Gain: 6ke@6ToT

▶ Charge trapping: decrease of charge collection
▶ Irradiation of 130 μm thick sensor reduce the signal by 3 ToT units: $MPV_{irr} \simeq 6$ $MPV_{unirr} \simeq 9$
▶ At $3 \times 10^{15} n_{eq}/cm^2$, charge collection is reduced by $\simeq 33\%$ compared to unirradiated sensors.

landau (x) gauss convolution

$V_{bias} = 400V$
$V_{bias} = 450V$
$V_{bias} = 500V$
$V_{bias} = 550V$
$V_{bias} = 600V$
Thr = 700e
Gain: 4ke@8ToT

▶ Evolution of the depletion with voltage for highly irradiated sensor: $1 \times 10^{16} n_{eq}/cm^2$

▶ At 600V, MPV$\simeq$ 8.5 so induced charge close to 4000 e. Degradation of charge collection efficiency of $\simeq$ 50% compared to unirradiated sensor

Sensor efficiency vs bias voltage and fluence up to $1 \times 10^{16} n_{eq}/cm^2$
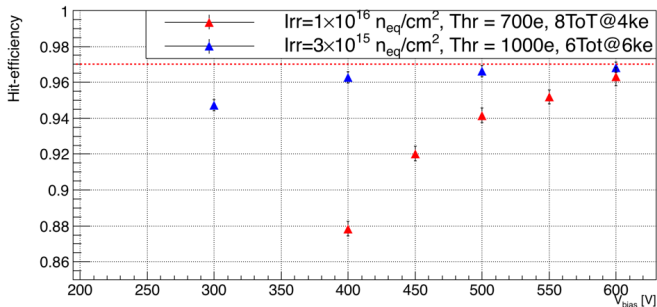
▶ At $1 \times 10^{16} n_{eq}/cm^2$ and 600V, efficiency is $96.32 \pm 0.5\%$, quite close to the 97% ATLAS requirement

▶ At $3 \times 10^{15} n_{eq}/cm^2$ and 600 V, efficiency reaches 97%

NB: Low threshold gives better results

Conclusions

- ▶ Thanks to the Active edge technology, the edge region is efficient above 97% up to $70\mu m$ from last pixel
- ▶ Thin sensors highly efficient after irradiation: $\simeq 96.5\%$ at $1 \times 10^{16} n_{eq}/cm^2$ and higher than 97 % at $3 \times 10^{15} n_{eq}/cm^2$
- ▶ Thanks to **temporary metal** no permanent biasing structures, so **very homogeneous efficiency** in the whole pixel cell

To be tested in beam in autumn 2017:

- ▶ Combination of thin and active edge sensors (production 3) soon to be delivered.

Acknowledgements

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