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# Beam Test Results of **Thin n-in-p 3D and Planar Pixel Sensors** for the **High Luminosity LHC Tracker Upgrade at CMS**

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## HL-LHC & Phase-2 upgrade: why?

**Luminosity increased to 5x10$^{34}$ cm$^{-2}$s$^{-1}$**
(5 times the LHC design luminosity)

- ✔Increase Standard Model measurements precision
- ✔Increase discovery potential
- ✔Search for rare decays
- ✗Increase radiation dose (≤ 1.2 MGy)
  - → fluence ≤ **2.3x10$^{16}$ n$_{eq}$/cm$^2$**
- ✗Increase pile up (140 -200)

Inner Tracker upgrade

## Development of new silicon pixel sensors

- **100 µm and 130 µm thick** (current 285 µm)
- **n-in-p type** (current n$^+$-in-n)**, 6" wafers**
- single sensor bump bonded to the PSI46dig readout chip

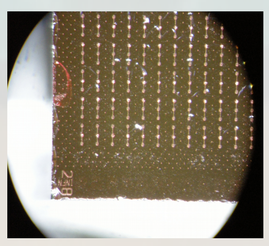
Results from beam tests performed at FTBF (Fermilab Test Beam Facility) using protons @ 120GeV

First results on **3D** sensors with **different** pixel **cell disegn**

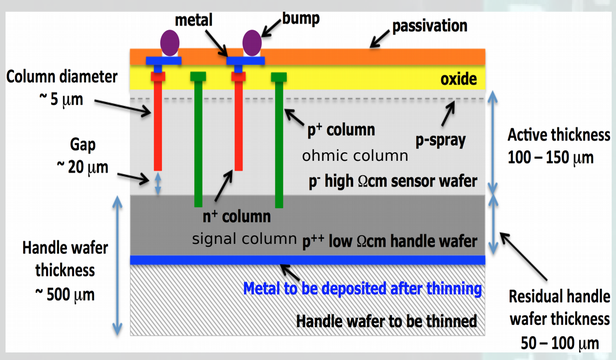
**Planar** sensor irradiated up to **3x10$^{15}$ n$_{eq}$/cm$^2$**

(Results presented here are limited by the radiation hardness of the present readout chip)

## **3D** devices (**130 µm thickness**) are single sided, realized with a top-side process implemented by FBK: **DRIE** (Deep Reactive Ion Etching). This technique allows a very good control on column depths.



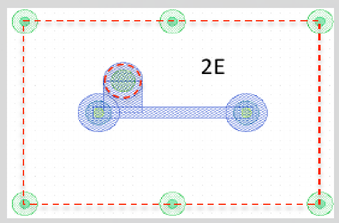
3D 100 µm x 150 µm pixel with 3E (Junction Column) configuration and Bump On Column option



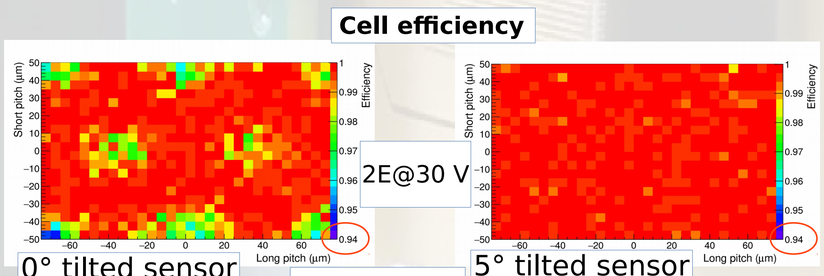

- various designs for the charge collecting electrodes
- pitch sizes:
  - 100 µm x 150 µm
  - **50 µm x 50 µm**
  - **25 µm x 100 µm**
- different bump pad locations

## **3D** sensors overall **efficiency > 99%**

**Cell efficiency**

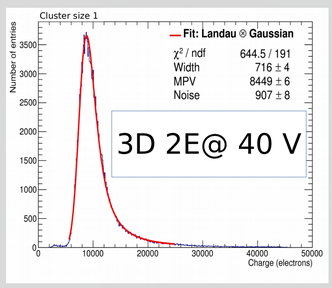



W76-1-56B – 100 µm x 150 µm




0° tilted sensor | 2E@30 V | 5° tilted sensor

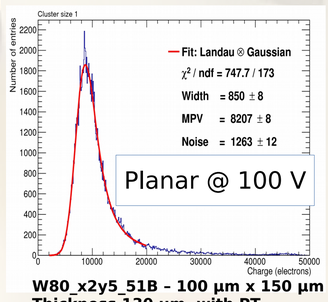
red≥99%




3D 2E@ 40 V

**3D** sensors collect the **same amount of charge** as planar sensors at a **lower bias voltage**

MPV ~8300 e$^-$




Planar @ 100 V

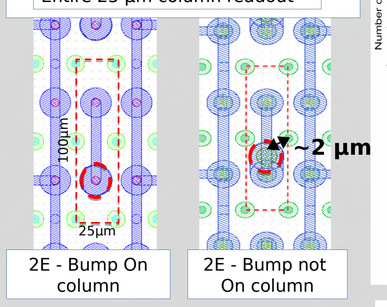
W80_x2y5_51B – 100 µm x 150 µm
Thickness 130 µm, with PT

**Small Pitch pixels**

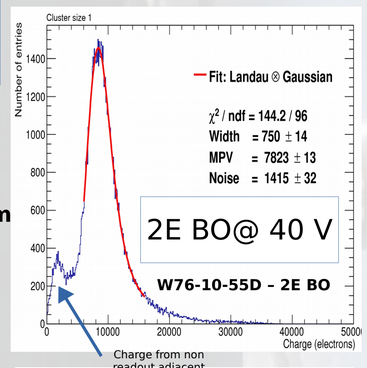
(only one out of six Pixels Cells is connected to PSI46 ROC)

### 25 µm x 100 µm

Entire 25 µm column readout

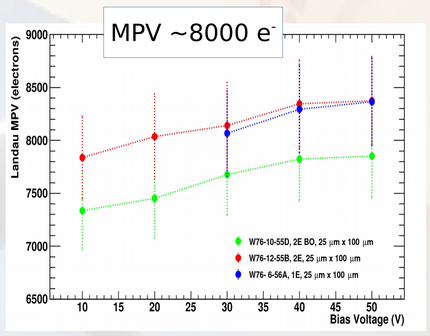



2E - Bump On column | 2E - Bump not On column




2E BO@ 40 V

W76-10-55D – 2E BO

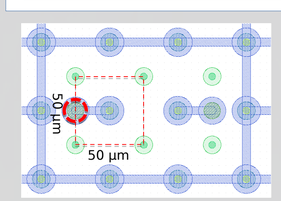


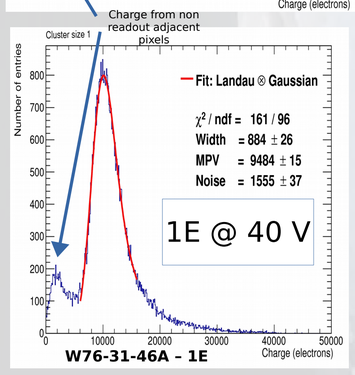

MPV ~8000 e$^-$

**Landau MPV vs Bias Voltage**

### 50 µm x 50 µm

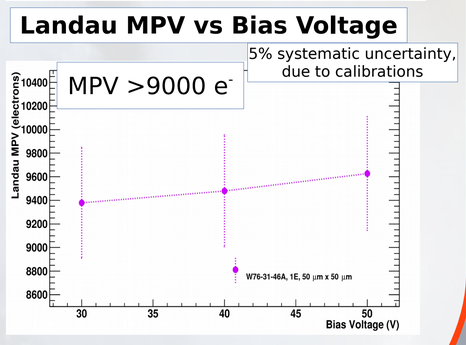
2 adjacent 50 µm pixels readout




1E @ 40 V

W76-31-46A – 1E



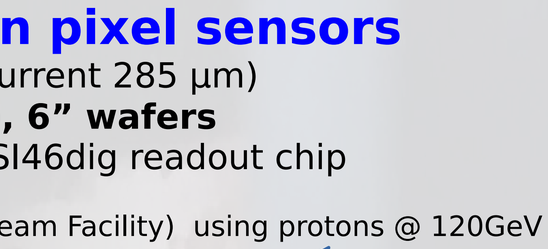

MPV >9000 e$^-$

5% systematic uncertainty, due to calibrations

**Small pitch pixels can be produced and work fine**

## **Planar** sensor **irradiated** with **protons** @ **3x10$^{15}$** n$_{eq}$/cm$^2$

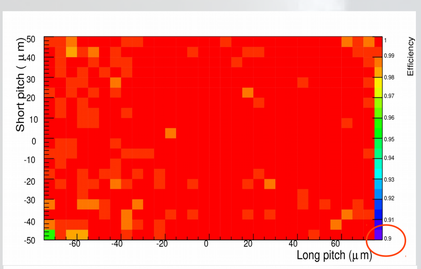
- FP50 (w30_x4y7_62D) :
  - **no** Punch Through
  - **50 µm gap** between n+ implants
  - Active thickness 100 µm




$$\varepsilon = \frac{\text{\# of tracks reconstructed by the telescope having a corresponding hit on the detector}}{\text{\# of total tracks reconstructed by the telescope and traversing the detector}}$$

& check for track pointing misplacements

**Cell efficiency:**
ε as a function of the hit coordinates on a single cell, averaged on all the cells




Before irradiation @ 40 V

red≥99%

**Efficiency > 99%**
Before irradiation
&
**Efficiency > 90%**
after irradiation

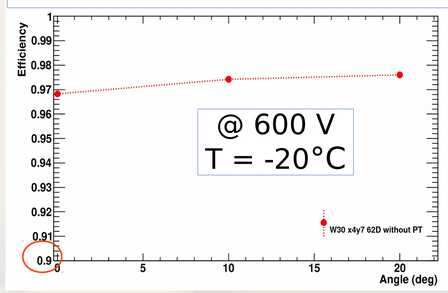



After irradiation @ 600 V

red≥90%

**Charge sharing**

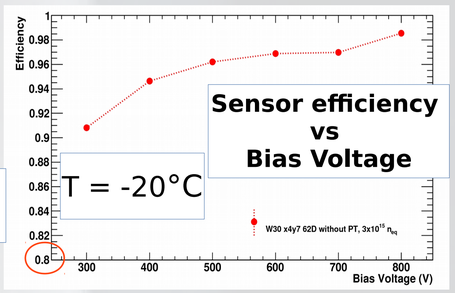
**Sensor efficiency vs Tracks angle**




@ 600 V
T = -20°C

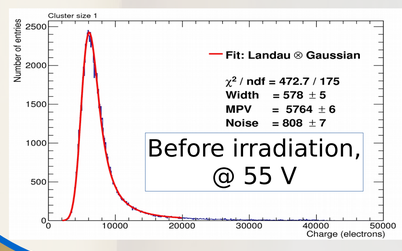
After irradiation

Efficiency > 90%, Up to ~98%

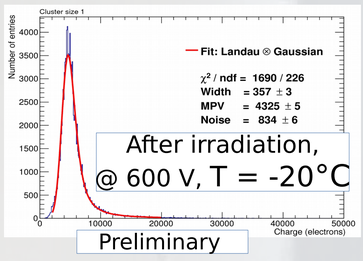



T = -20°C

**Sensor efficiency vs Bias Voltage**




Before irradiation, @ 55 V




After irradiation, @ 600 V, T = -20°C

Preliminary

**CCE ~ 75%**

## Summary & Outlook

- Thin **planar** pixel sensor:
  - **Before irradiation efficiency > 99%**
  - **Efficiency > 90%** after proton irradiation to **3x10$^{15}$** n$_{eq}$/cm$^2$
  - **Charge Collection Efficiency ~ 75%**
- Thin **3D** columnar pixel sensors:
  - Same collected **charge** & **efficiency** as planar sensors at a lower bias voltage
  - **Small pitch sensors (25 µm x 100 µm & 50 µm x 50 µm)** are **promising candidates** for inner layer tracker upgrade at **HL-LHC**
- **Irradiations are ongoing:**
  - With protons & neutrons
  - Up to 1.5x10$^{16}$ n$_{eq}$/cm$^2$ for both planar and 3D sensors
- New readout chip (RD53A, 65nm technology) with 50 µm x 50 µm pitch will be available to test highly irradiated and small pitch sensors

Additional material can be found here:

- Meschini, M.; Dalla Betta, G. F.; Boscardin, M.; Calderini, G.; Darbo, G.; Giacomini, G.; Messineo, A.; Ronchin, S. "The INFN-FBK pixel R&D program for HL-LHC", doi:10.1016/j.nima.2016.05.009
- Dalla Betta, G. F.; Boscardin, M.; Darbo, G.; Mendicino, R.; Meschini, M.; Messineo, A.; Ronchin, S.; Sultan, D. M. S.; Zorzi, N.; "Development of a new generation of 3D pixel sensors for HL-LHC", doi:10.1016/j.nima.2015.08.032
- Dalla Betta, G. F. and others; "The INFN–FBK "Phase-2" R&D program", doi:10.1016/j.nima.2015.08.074
- Sultan, D. M. S.; Dalla Betta, G. F.; Mendicino, R.; Boscardin, M.; Ronchin, S.; Zorzi, N.; "First Production of New Thin 3D Sensors for HL-LHC at FBK", doi:10.1016/j.nima.2015.08.074
- Dalla Betta, G. F.; Boscardin, M.; Mendicino, R.; Ronchin, S.; Sultan, D. M. S.; Zorzi, N.; "Development of new 3D pixel sensors for phase 2 upgrades at LHC", doi:10.1109/NSSMIC.2015.7581946