10th Beam Telescopes and
Test Beam Workshop

# Test Beam Results of Highly Irradiated 3D and Planar Pixel Sensors Interconnected to the RD53A Readout Chip

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On behalf of the CMS Tracker Group

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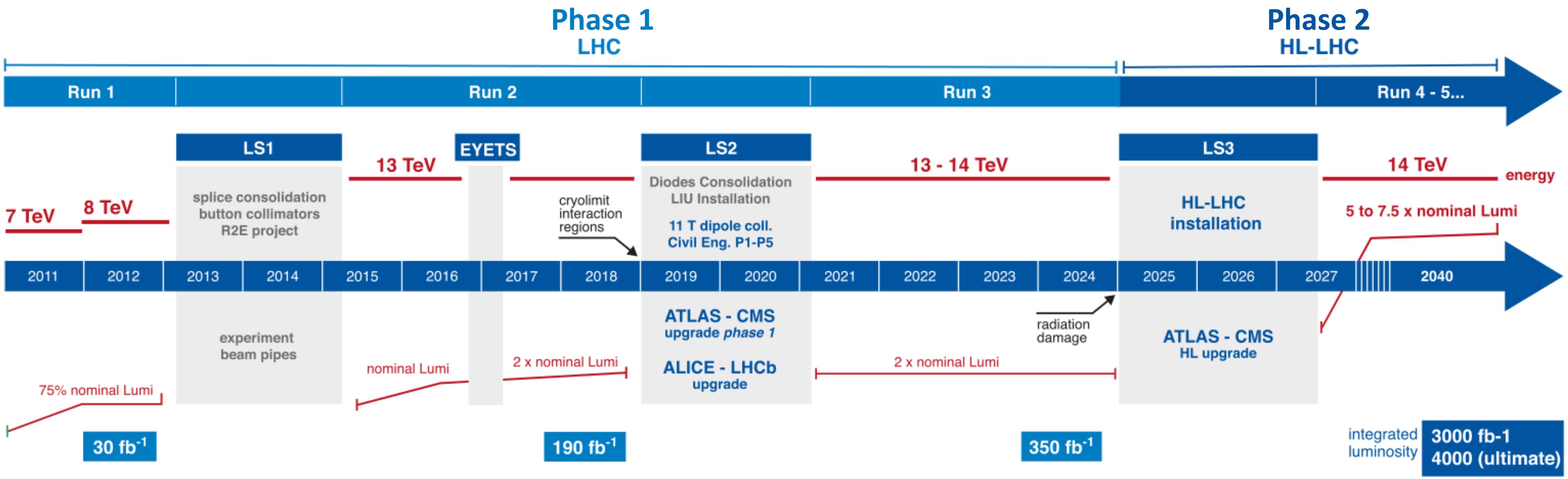
# High Luminosity LHC

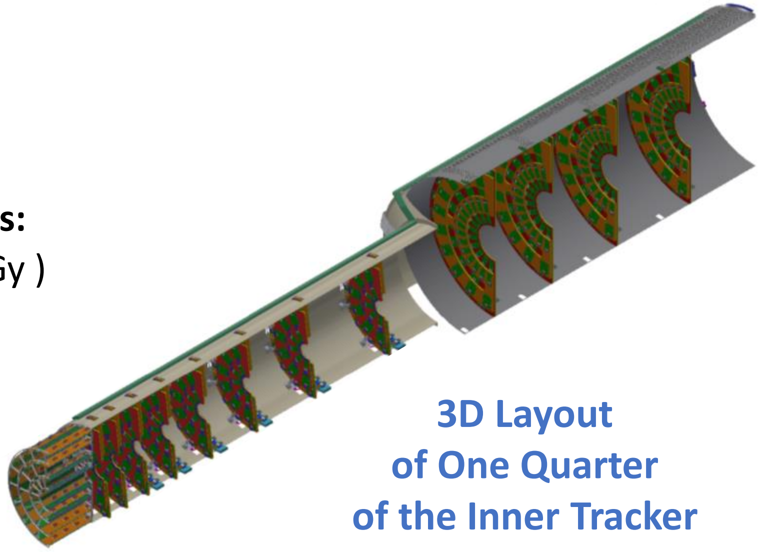
- HL-LHC will be installed between 2025 and 2027 → CMS will restart data taking in 2027 (start of Phase 2)
- Luminosity $\mathcal{L}$ will reach $7.5 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Collect up to $\mathcal{L}_{\mathrm{int}} = 4000\ \mathrm{fb}^{-1}$ in 10 years (to be compared with the expected $500\ \mathrm{fb}^{-1}$ at the end of Phase 1)
  - Study rare events of the Standard Model or search for new physics
- All the CMS detectors will be upgraded → Hit rate up to $3.2\ \mathrm{GHz\ cm}^{-2}$
  - The silicon tracker will be completely replaced



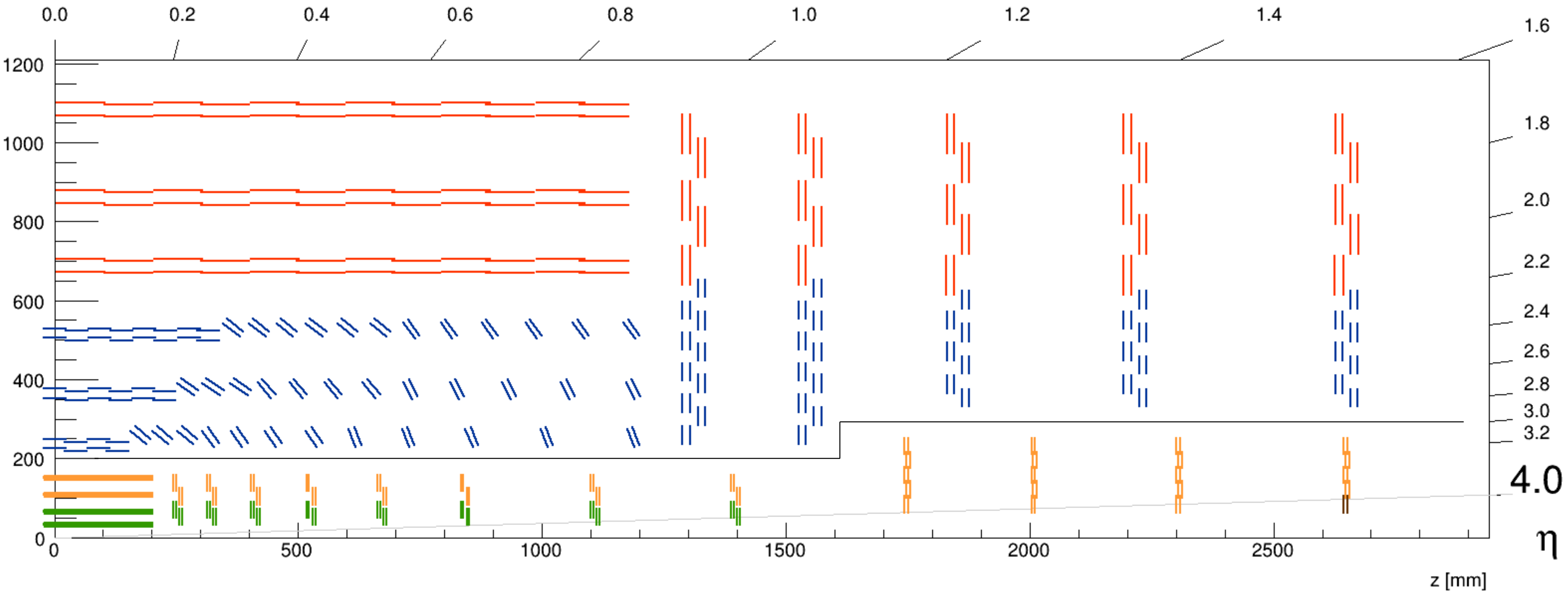
# The CMS Tracker Upgrade

- Composed by two sections:
  - **Inner Tracker** → Pixel detectors (this presentation)
    - $4.9\ \mathrm{m}^2$ of pixel surface and $2 \times 10^9$ channels
    - Inner layer at only 30 mm from the beam line
  - **Outer Tracker** → Strip and macro-pixel detectors

**Expected fluence (dose)**
**after 10 years of operations:**
$35 \times 10^{15}\ \mathrm{n_{eq}cm^{-2}}$ ( 19 MGy )



**3D Layout of One Quarter of the Inner Tracker**



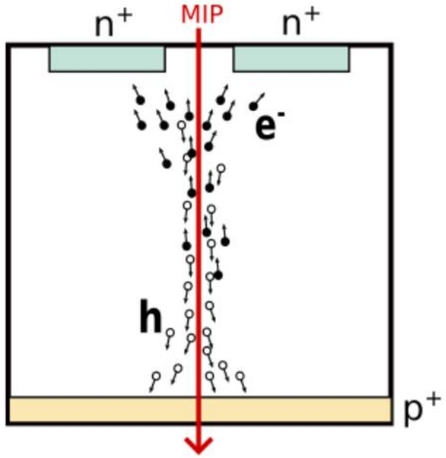
**Side View of One Quarter of the future CMS Tracker**

# Silicon Pixel Sensors

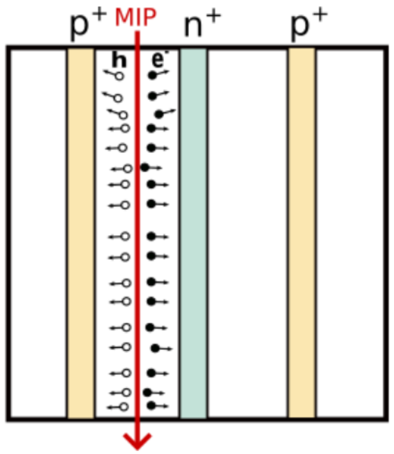
- Two types of sensors are considered for the new tracker:
  - Standard “planar” pixel sensors
  - **3D** pixel sensors → Higher **radiation resistance**
    - New technology: considered only for the innermost layer
- In 3D sensors the drift path is perpendicular to the active thickness
  - Short drift distance of charge carriers: $\sim 30 - 50\ \mu\mathrm{m}$ (vs. $100 - 150\ \mu\mathrm{m}$ for planar)
- 3D sensors have many advantages with respect to planar sensors:
  - Smaller bias voltages needed to deplete the sensor
  - Reduced trapping probability in irradiated sensors

- **Active thickness** (for both 3D and planar pixel sensors): $150\ \mu\mathrm{m}$
- **Pixel size** (pitch): $50 \times 50\ \mu\mathrm{m}^2$ or $25 \times 100\ \mu\mathrm{m}^2$ (six times smaller w.r.t. the present CMS tracker)
  - $\mathbf{25 \times 100\ \mu m^2}$ is now the baseline for the whole Inner Tracker

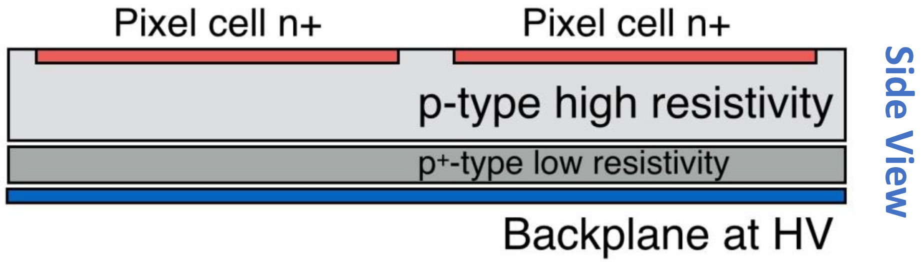
**Planar Pixel Sensor**



**3D Pixel Sensor**

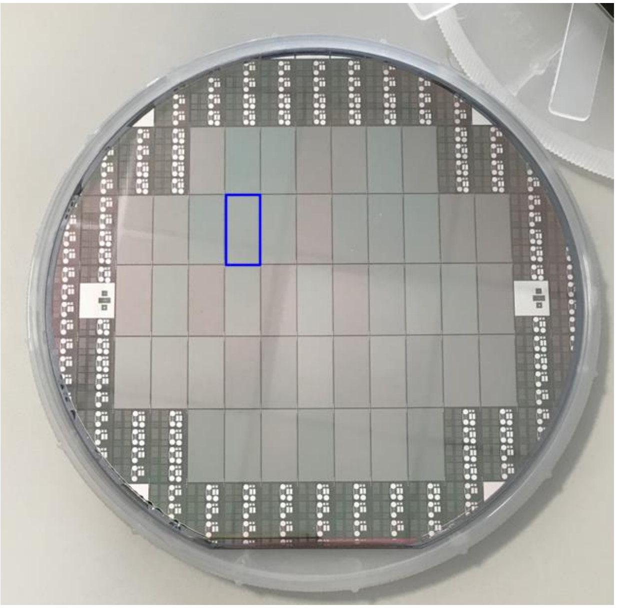


# Planar Pixel Sensors



- The planar pixel sensors studied in this presentation are made by:
  - An active area, the substrate ($p$-doped, high resistivity silicon)
  - Superficial $\boldsymbol{n^+}$ **implants** used as collecting **electrodes**
- A low resistivity silicon layer is bonded to the high resistivity substrate (Silicon-Silicon)
  - Mechanical support for the silicon wafer during production
  - Ohmic contact for the $p-n$ junction
  - Thinned and metallized after production → Total sensor thickness around $250\ \mu\text{m}$
  - “Direct Wafer Bonding” (DWB) technique
- The bias voltage is applied to the ohmic contact, on the backside of the sensor

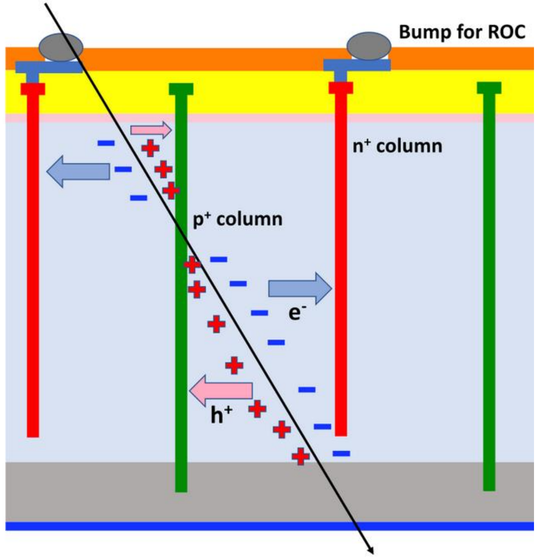
Silicon Wafer



# 3D Pixel Sensors

- 3D pixel sensors studied in this presentation are fabricated with the DRIE technique
- Columnar implants penetrate deep into the substrate from the same silicon face
  - 5 µm diameter holes in silicon
  - The columns are doped differently: $p^+$ and $n^+$
  - $p^+$ columns reach the backside of the sensor, hence the bias voltage
  - $n^+$ columns are connected to the readout chip
- A pixel “cell” is delimited by $p^+$ columns
  - $n^+$ column in the center of the cell
- Pixel sensors studied in this presentation (planar and 3D) were developed in a collaboration between INFN and FBK foundry (Trento)

**Side View**



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**Top Views**

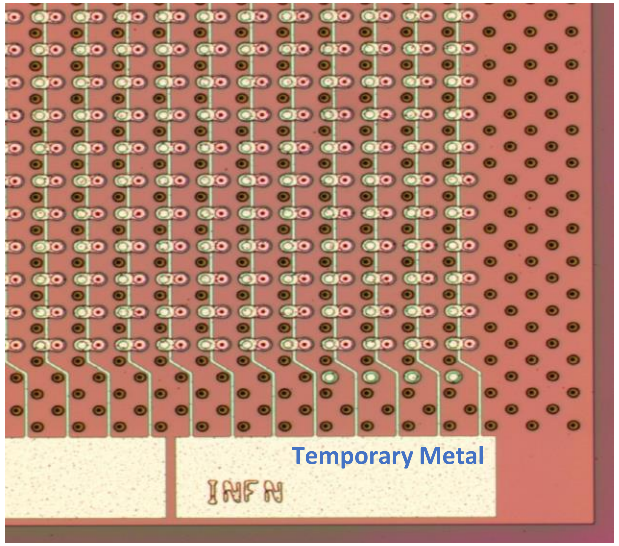
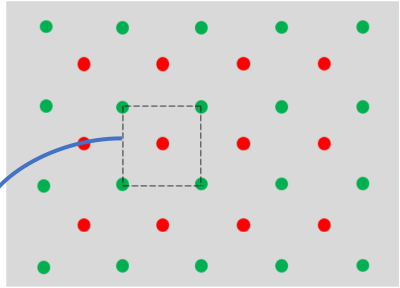


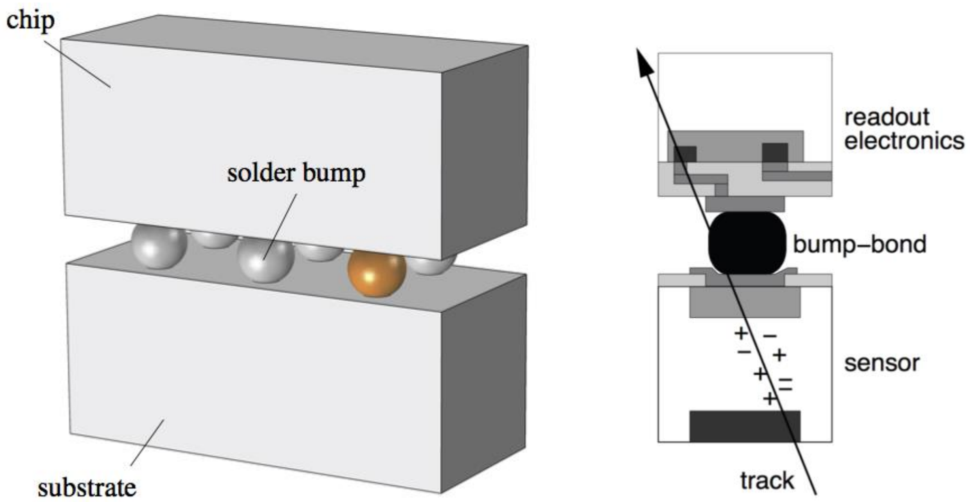
Photo from Wafer



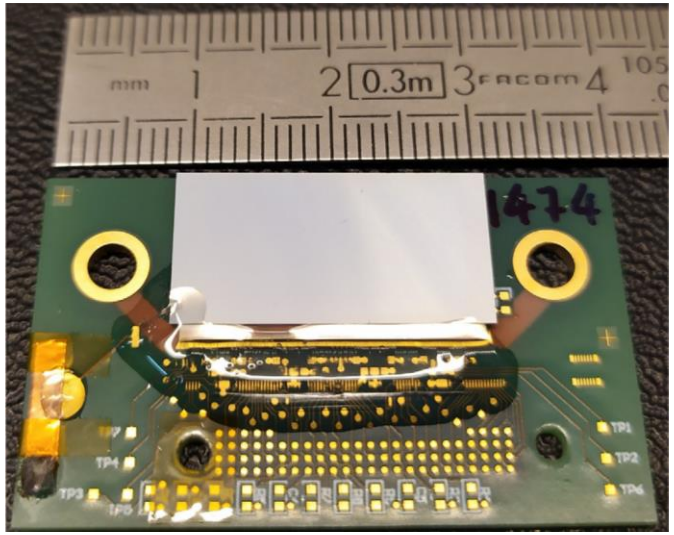
**Pixel Cell**

# The Readout Chip

- The ReadOut Chip (ROC) is coupled to the sensor
  - Bump bonding technique
  - Sensor + ROC → Pixel module
- RD53 chip project (collaboration between ATLAS and CMS)
  - 65 nm technology and $50 \times 50\ \mu\text{m}^2$ (single) cell size
  - Radiation hard (certification up to 5 MGy)
- RD53A ($\sim {}^{1}/_{2}$ size of the final chip) is the first prototype
  - 76800 pixel channels (only the central zone was readout for this presentation)
  - Used for R&D in the last years
- Various calibrations are needed to operate the pixel modules
  - For instance, the pixels channels can be tuned to average thresholds below 1000 electrons (with a dispersion of $\sim$ 50 electrons) before irradiation



**Bump Bonding**

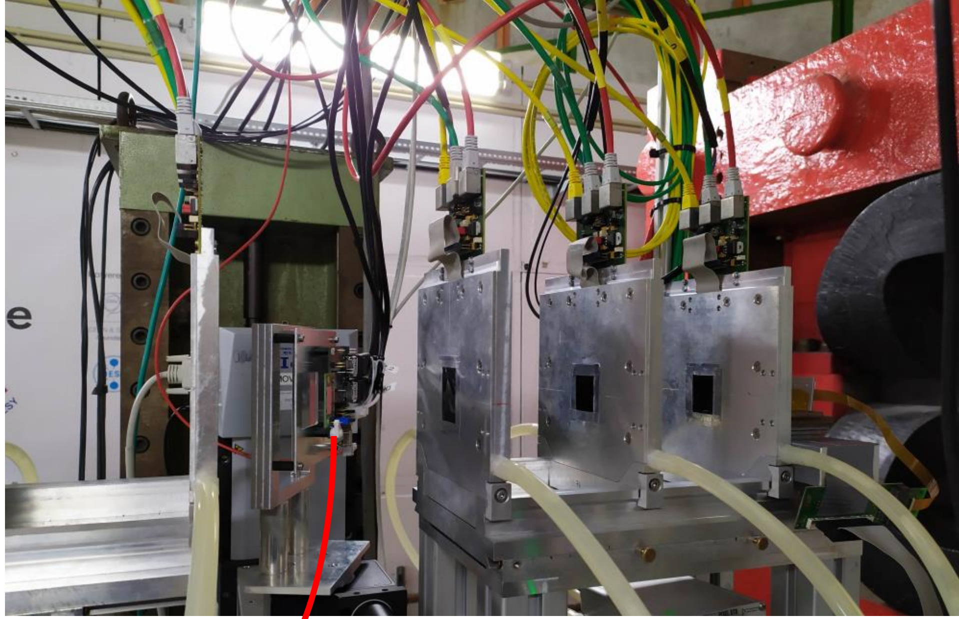


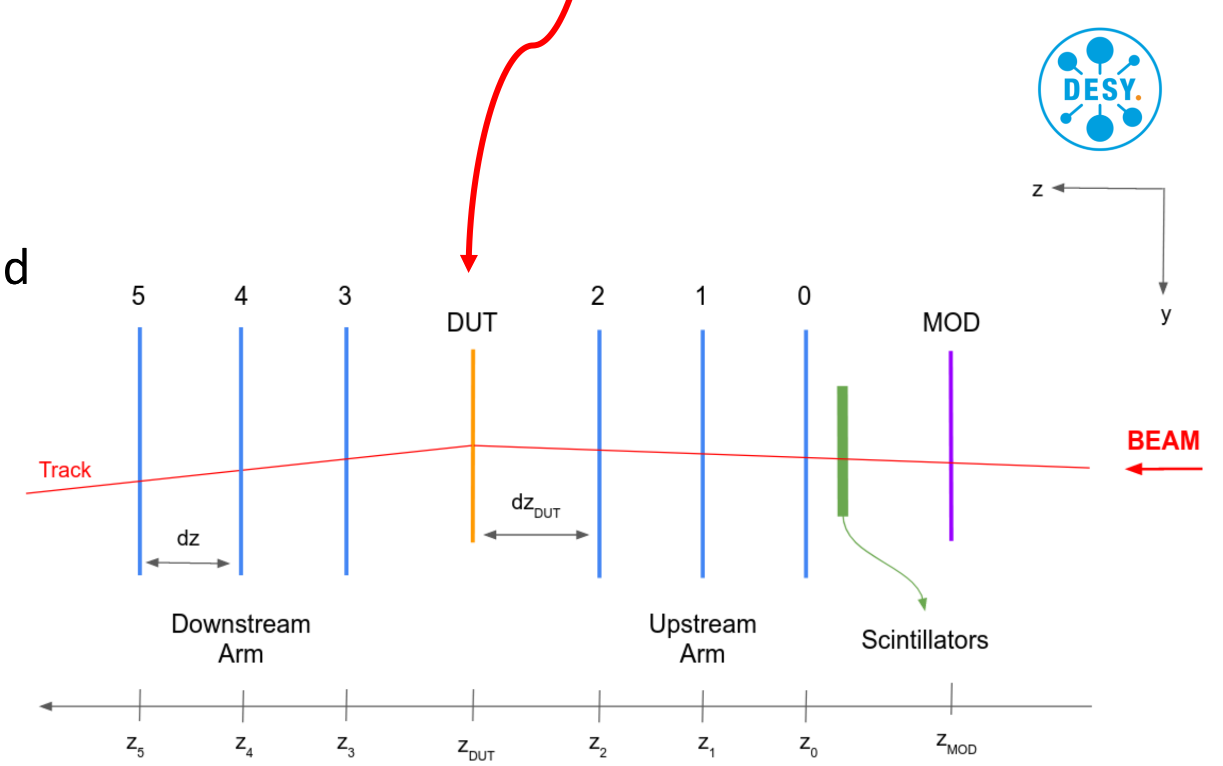
**Sensor + RD53A ROC assembly**

# The DESY Test Beam Facility

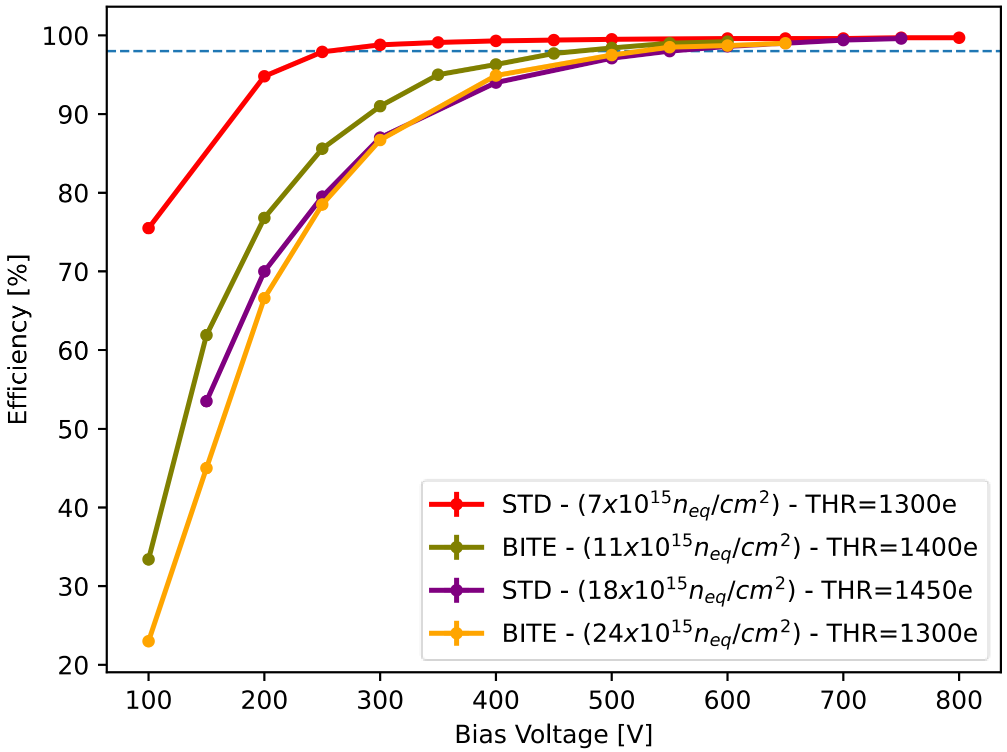
- Several Test Beam experiments at DESY…
  - …to fully characterize 3D and planar pixel modules
  - Test beam facility ($5.2\ \mathrm{GeV}$ electron beam)
- Telescope: EUDET type (MIMOSA26 pixel sensors)
  - Six planes of tracking detectors
- DUT: Device Under Test, our tested pixel module

- Pixel modules are tested before and after being irradiated
  - To fluences equivalent to those expected in HL-LHC
- Irradiated DUTs are kept inside a cooling box
  - Stable temperature of about $-27\ ^\circ\mathrm{C}$
  - Compensate the effects of radiation damage

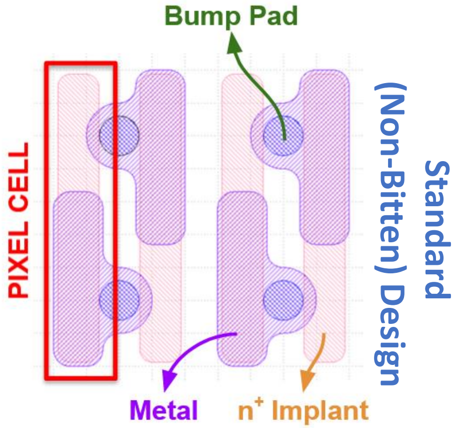




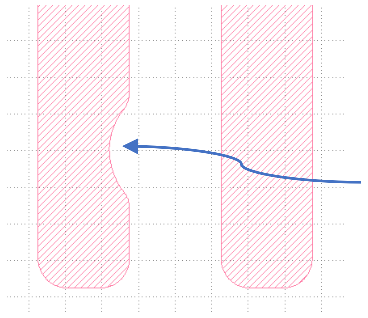
# Irradiated Planar Pixel Modules – Hit Detection Efficiency



- Four $25 \times 100\ \mu\mathrm{m}^2$ **irradiated** planar pixel modules (Standard and Bitten designs) were tested on beam
- Hit detection efficiency vs. the bias voltage
- In order to reach an efficiency $> 98\%$ :
  - $\mathrm{V_{bias}} > 400\ \mathrm{V}$ after a fluence of $\mathbf{11 \times 10^{15}\ n_{eq}cm^{-2}}$
  - $\mathrm{V_{bias}} > 600\ \mathrm{V}$ after a fluence of $\mathbf{23 \times 10^{15}\ n_{eq}cm^{-2}}$
- Planar pixel modules in the innermost tracker layers can survive for more than half the HL-LHC program
  - However, very high bias voltages are required
  - Cooling becomes challenging



**Standard (Non-Bitten) Design**

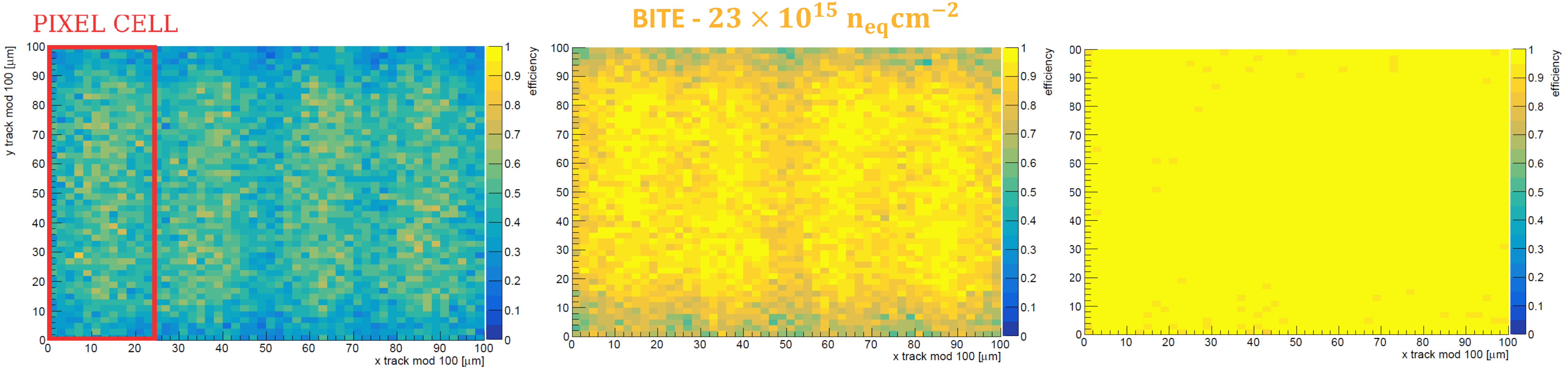


**Bitten Design: Zoom-in of the bitten $n^+$ implant**

**Effectively reduces cross-talk in fresh $25 \times 100\ \mu\mathrm{m}^2$ sensors**

# Irradiated Planar Pixel Modules – Hit Detection Efficiency

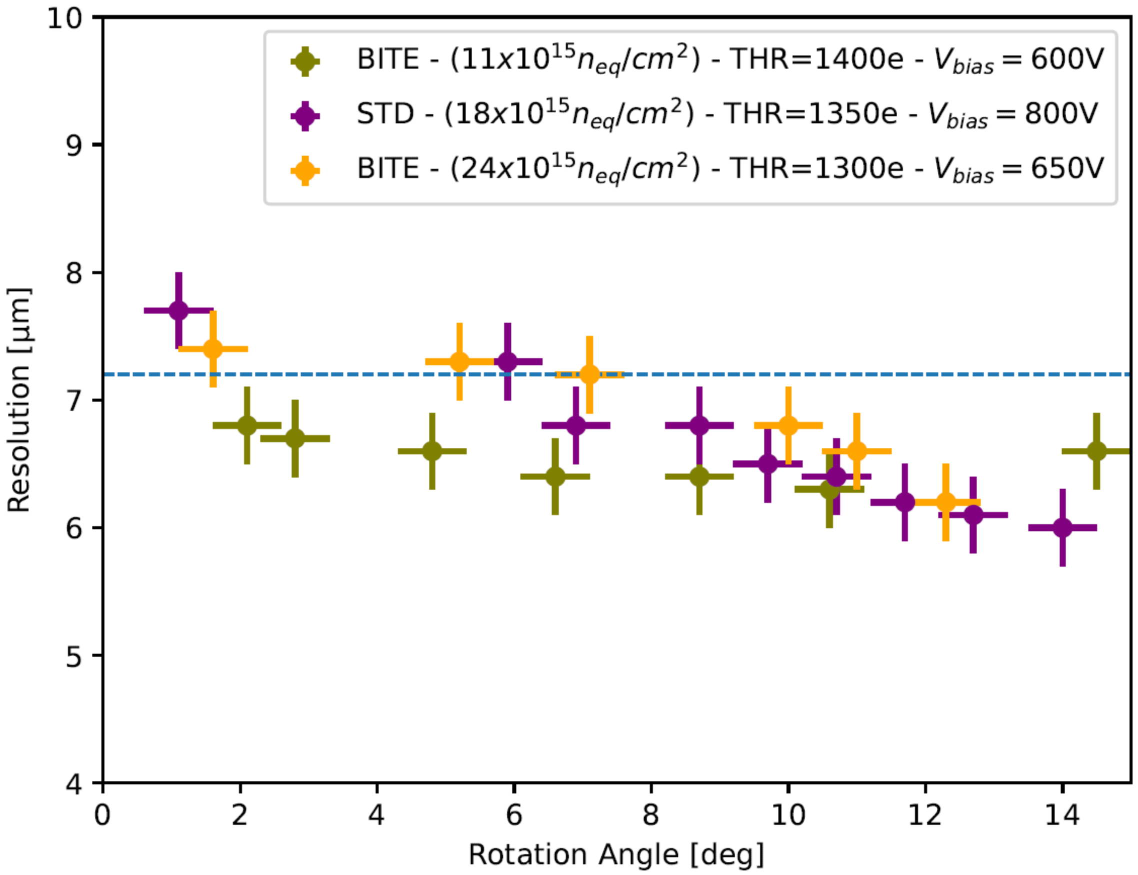
**BITE - $23 \times 10^{15}\ \mathrm{n_{eq}cm^{-2}}$**



$\mathrm{V_{bias}} = 150\ \mathrm{V}$ $\mathrm{V_{bias}} = 350\ \mathrm{V}$ $\mathrm{V_{bias}} = 650\ \mathrm{V}$

- Hit detection efficiency map for a $4 \times 1$ pixel grid, with increasing $\mathrm{V_{bias}}$ and **perpendicular track incidence**
- At low $\mathrm{V_{bias}}$ the efficiency is lower at the intersection of adjacent pixels
  - Due to charge sharing between pixels and charge trapping in highly irradiated silicon
- By increasing $\mathrm{V_{bias}}$ the efficiency increases and becomes more uniform across the pixel cells
  - More depleted sensor and higher electric field → Higher collected charge and higher detection efficiency

# Irradiated Planar Pixel Modules – Resolution



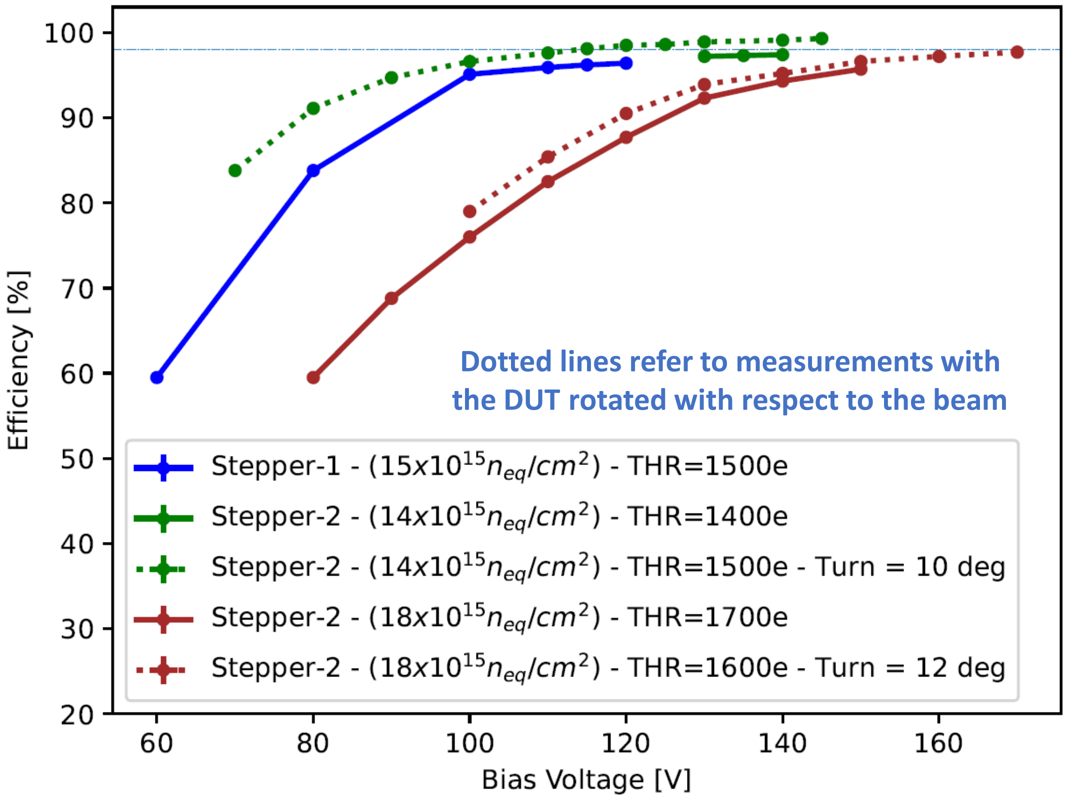
The horizonal line marks the digital resolution

- Resolution vs. rotation angle (w.r.t. the beam)
  - Rotation around the 25 µm pitch

- Due to the presence of the cooling box, only the upstream telescope planes are used in reconstruction
  - Telescope resolution estimated with simulation…
  - …and subtracted in quadrature

- In fresh modules, resolution is 2 µm at the optimal angle
- In irradiated modules the resolution is deteriorated
  - Due to charge trapping → Lower cluster size
  - However, resolutions close to 6 µm can be achieved
  - Despite the extreme irradiation fluences

# Irradiated 3D Pixel Modules – Hit Detection Efficiency



Two FBK 3D productions: **Stepper-1** and **Stepper-2**

(Step-And-Repeat photolithography technology).

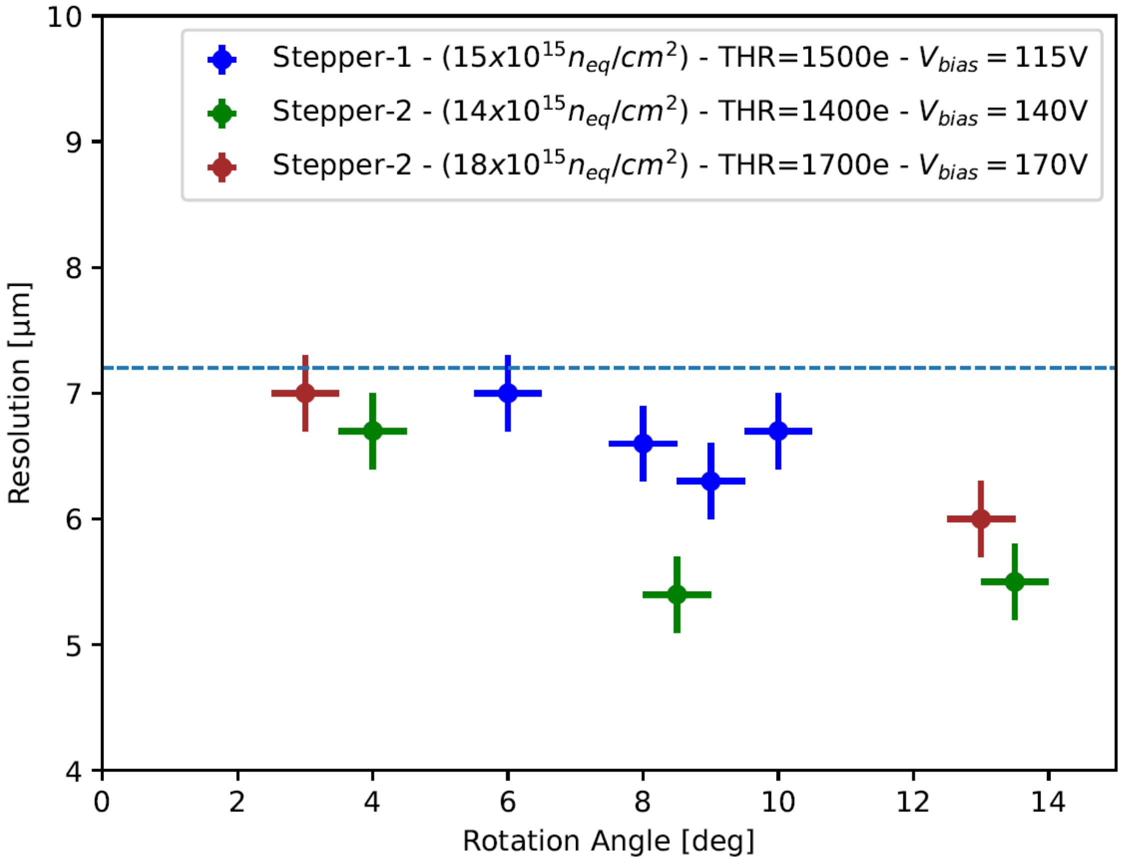
The pixel design is the same, but in Stepper-2 the distance between $n^+$ columns and the backside of the sensor was increased.

- Three $25 \times 100\ \mu\mathrm{m}^2$ **irradiated** 3D pixel modules (Stepper-1 and Stepper-2 productions) were tested on beam

- Hit detection efficiency vs. the bias voltage
- In order to reach an efficiency $> 98\%$ :
  - $\mathrm{V_{bias}} > 110\ \mathrm{V}$ after a fluence of $\mathbf{15 \times 10^{15}\ n_{eq}cm^{-2}}$
  - $\mathrm{V_{bias}} > 160\ \mathrm{V}$ after a fluence of $\mathbf{18 \times 10^{15}\ n_{eq}cm^{-2}}$

- Higher efficiency when the DUT is rotated w.r.t. the beam
  - The columns are made by passive material → Inefficiencies
  - By rotating the DUT the inefficiencies are recovered, since incident particles always escape the passive material

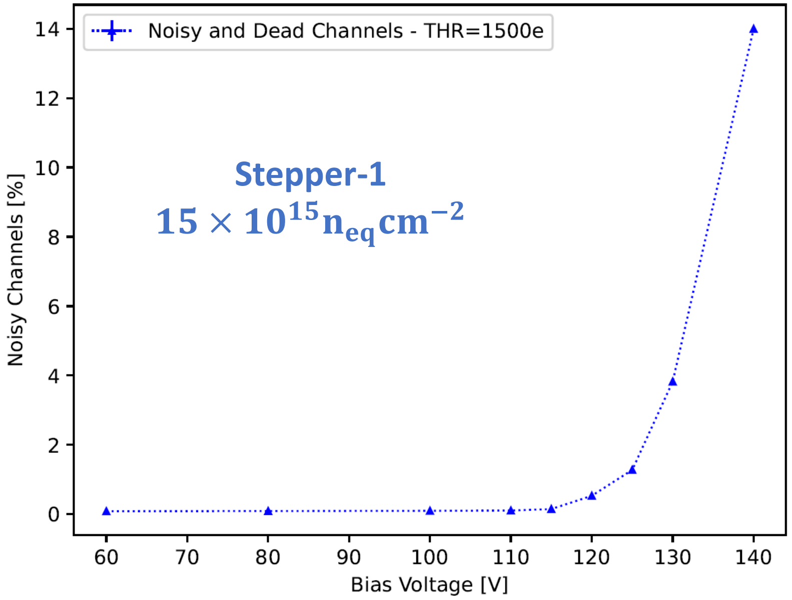
# Irradiated 3D Pixel Modules – Resolution

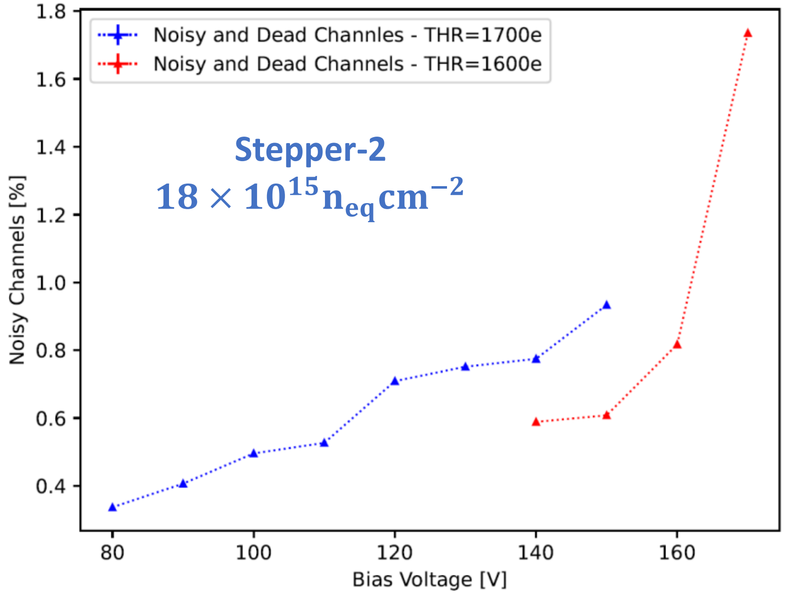


The horizonal line marks the digital resolution

- Resolution vs. rotation angle (w.r.t. the beam)
  - Rotation around the 25 μm pitch
- Telescope resolution is estimated from simulation
- In fresh modules, resolution is 2 μm at the optimal angle
- In irradiated modules the resolution is deteriorated
  - However, resolutions close to 6 μm can be achieved
  - Despite the extreme irradiation fluences
- Compatible results w.r.t. planar pixel modules

# Irradiated 3D Pixel Modules – Noisy Channels





- A sudden increase in the number of noisy channels was observed…
  - …at high bias voltages (greater than $130 - 170\ \mathrm{V}$, depending on the module)
  - The problem was more severe with **Stepper-1** modules ($> 10\%$ of channels)
- The cause is still under investigation: might be related to the very high TID
  - The modules were irradiated at KIT with $23$ MeV protons
  - The corresponding dose is extremely high: over $30$ MGy
  - The RD53A readout chip was design to withstand a maximum of $5$ MGy
- New irradiations are currently ongoing at CERN IRRAD facility
  - Up to $20 \times 10^{15}\ \mathrm{n_{eq}cm^{-2}}$

# Conclusions

- The CMS Inner Tracker project of the HL-LHC is extremely challenging
- Planar pixel modules showed excellent performance after being irradiated to $23 \times 10^{15}\ \mathrm{n_{eq}cm^{-2}}$
    - Although with very high bias voltages, $\mathrm{V_{bias}} > 600\ \mathrm{V}$
- 3D pixel modules irradiated to similar fluences showed similar performances
    - With lower bias voltages $\mathrm{V_{bias}} < 200\ \mathrm{V}$
    - The noisy channels behavior is still under study (new modules irradiations with lower TID are ongoing at CERN)
- The presented results will contribute to the optimization of the pixel detectors to be installed in CMS
    - 3D pixel modules will be installed in the innermost layer of the future CMS tracker