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FSP CMS
Erforschung von Universum und Materie

Performance of CMS Inner Tracker pixel assemblies for the Phase-2 Upgrade

B. Raciti | SiDet R&D Meeting – 26th Mar. 2024, DESY

CMS Inner Tracker upgrade for HL-LHC

The **High-Luminosity Large Hadron Collider** (HL-LHC) is an upgraded version of the LHC[1], foreseen to begin in 2028 onwards.

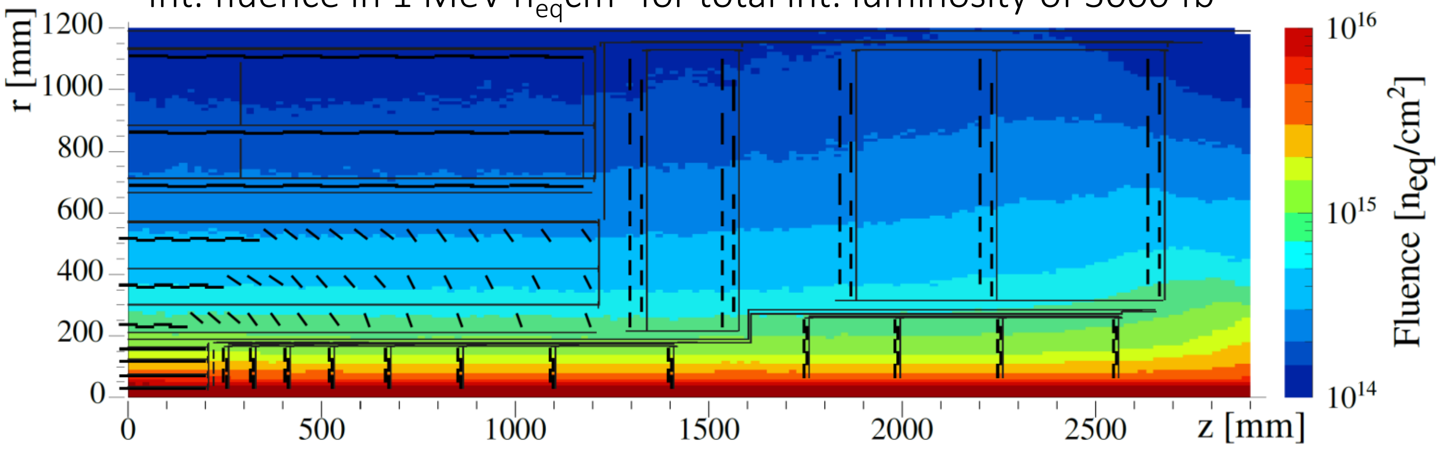
In the **HL-LHC** phase:

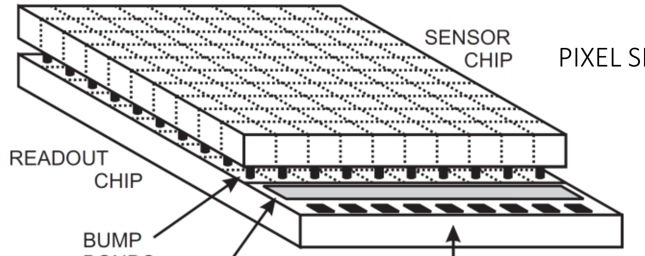
Luminosity: **7.5 x 10^{34} cm^{-2} s^{-1}**	Integrated luminosity: **3000 – 4000 fb^{-1}**	Pile-up: <μ> = **200**	ϕ_{max} planar modules $= 1 \times 10^{16}\ \mathrm{n_{eq}cm^{-2}}$

During the **Long-Shutdown 3**:

- **replacement** of CMS Outer (OT) and Inner Tracker (IT)
- IT pixel sensors: new **readout chip** (RD53C_CMS) and **sensor** design

Int. fluence in 1 MeV $n_{eq}cm^2$ for total int. luminosity of 3000 fb^{-1}





Stringent requirements for beginning → end of operation

[1] https://voisins.web.cern.ch/en/high-luminosity-lhc-hl-lhc

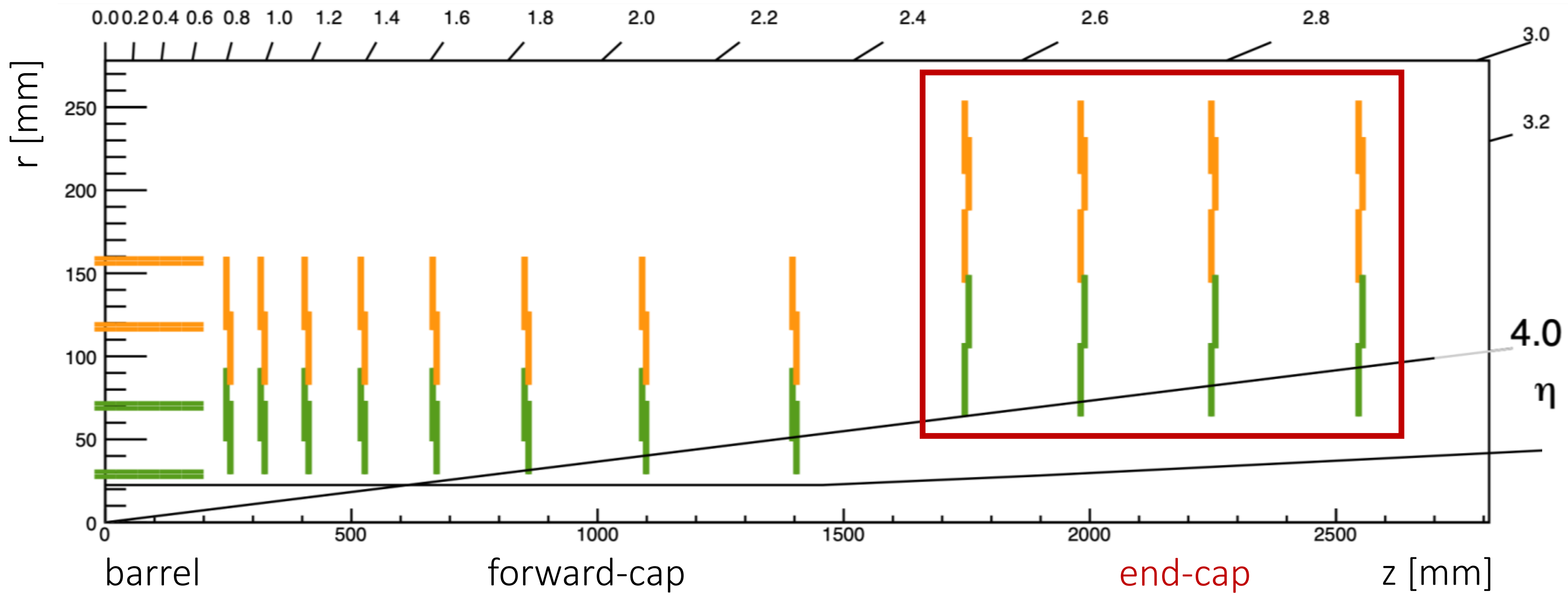
CMS Inner Tracker upgrade for HL-LHC

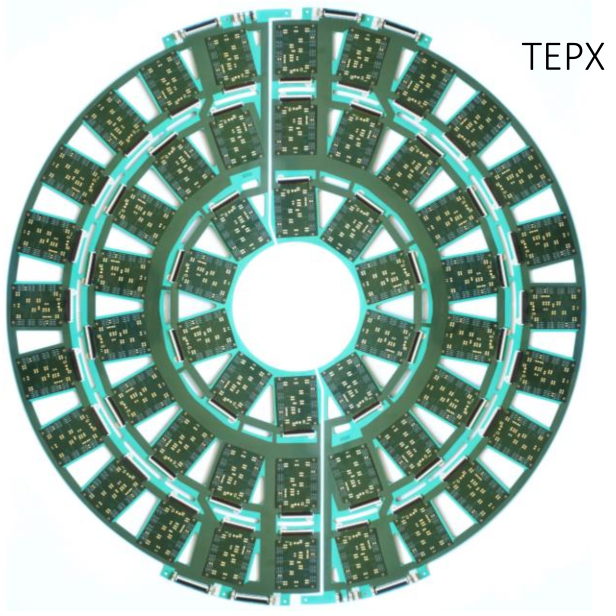
The Inner Tracker is divided into three sections: **barrel**, **forward-cap** and **end-cap**.

In total, it will feature:

- 1156 1x2 pixel modules → 2 readout-chips per module
- 2736 2x2 pixel modules → 4 readout-chips per module

500 TEPX 2x2 modules will be glued, wire-bonded and tested in Hamburg.





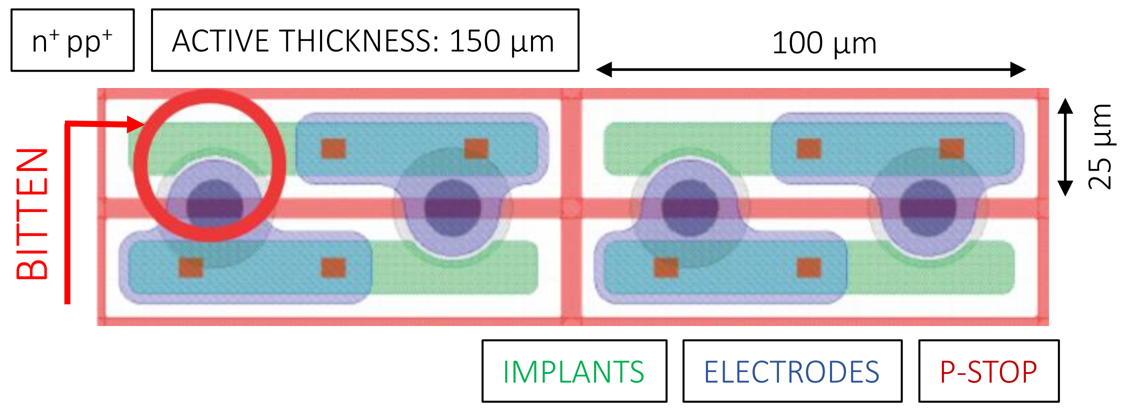
Hybrid pixel modules

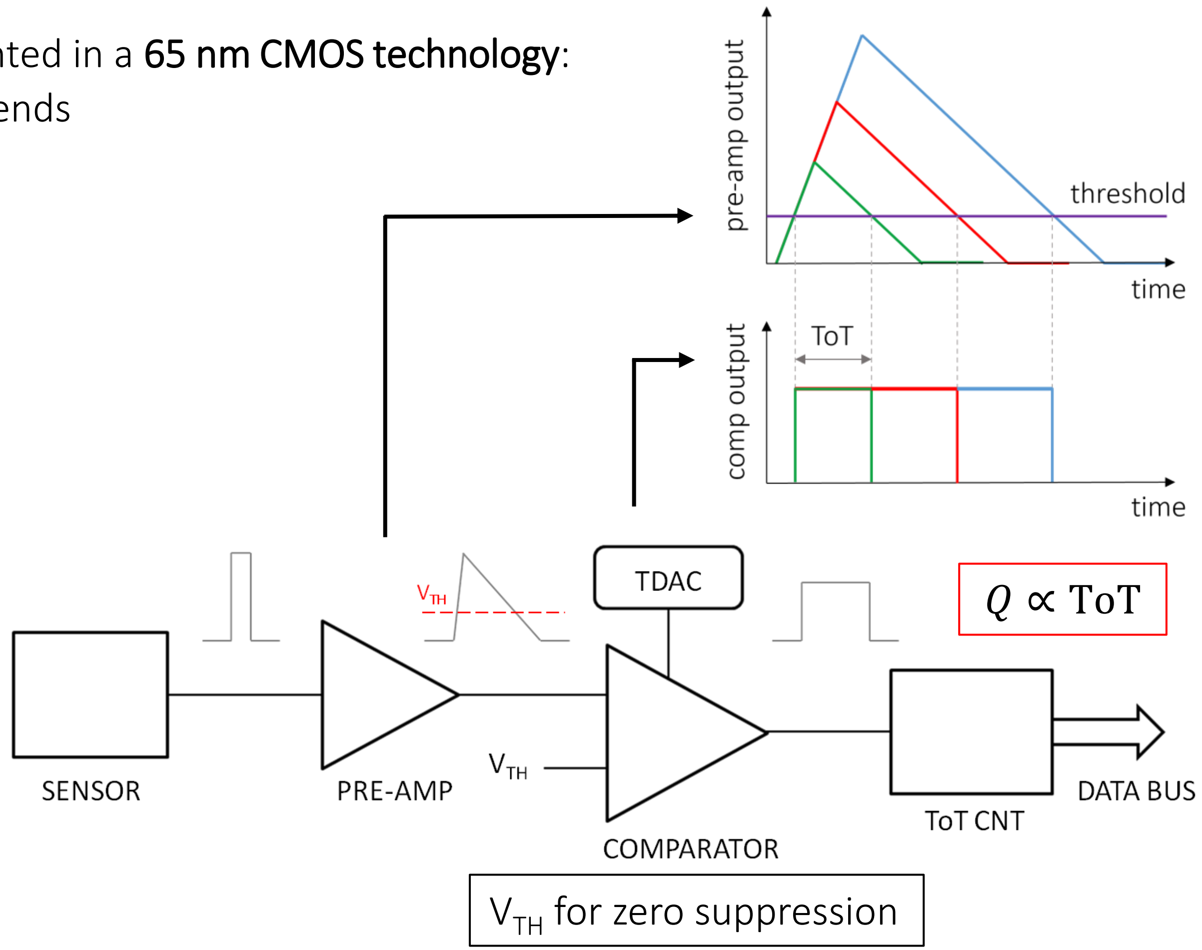
In hybrid pixel detectors the **sensor** and the **readout chip** are individually optimized and joined with bump-bonds.

Readout chip developed by the **RD53 Collaboration** and is implemented in a **65 nm CMOS technology**:

- **RD53A** → **half-size** pixel chip **demonstrator** with 3 different front-ends
- **RD53B _CMS** → **full-size prototype** chip
- **RD53C _CMS** → **production** chip

CMS chose the **linear front-end** design for the readout chip.





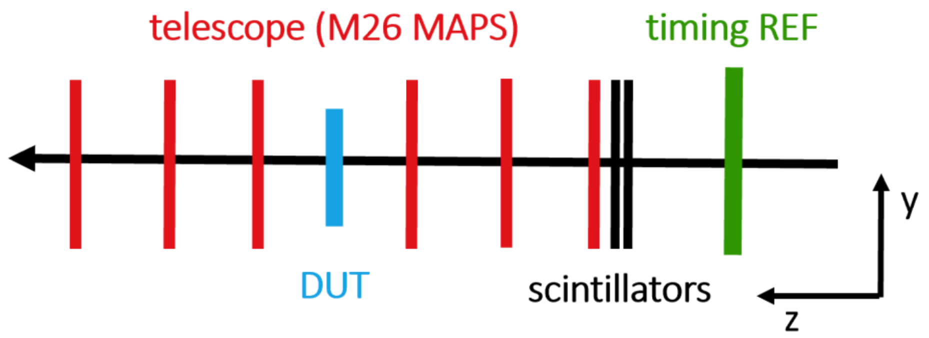
Experimental setup at DESY II

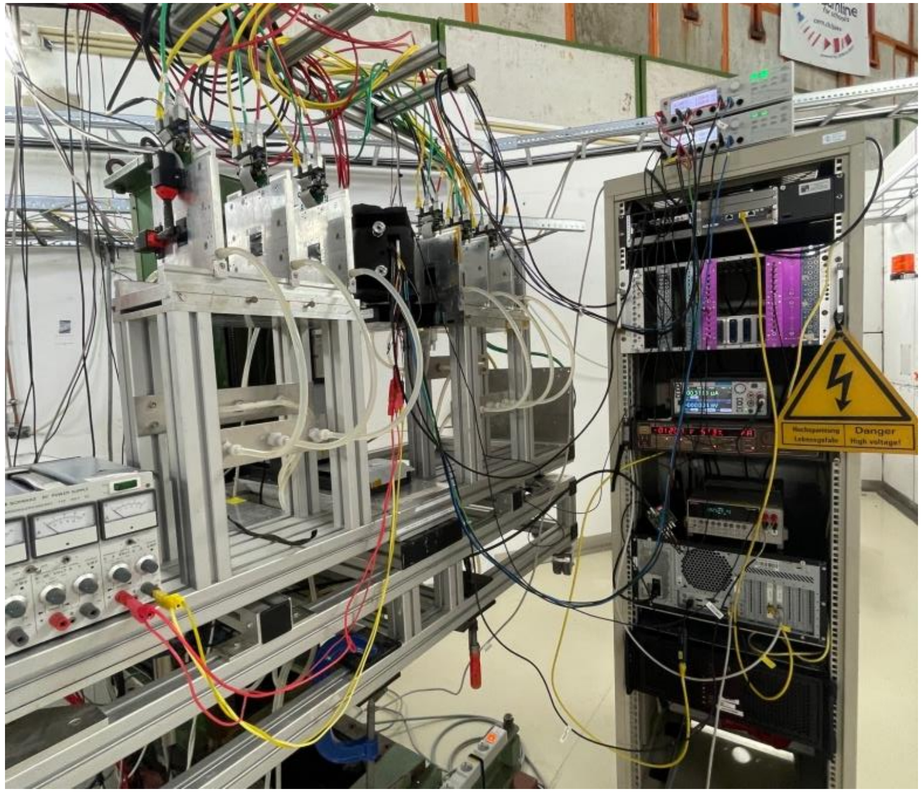
DESY test beam facility: e⁻/e⁺ beam with energies ranging from 1 to 6 GeV (data taken at 5.2 GeV)

Observables: $\varepsilon_{\text{hit}} = \frac{N^{\text{DUT}}_{\text{tracks}}}{N^{\text{total}}_{\text{tracks}}}$ $\quad \alpha = 1 - \frac{N^{\text{pxl}}_{\text{masked}}}{N^{\text{pxl}}_{\text{total}}}$ $\quad \varepsilon_{\text{hit assembly}} = \varepsilon_{\text{hit}} \times \alpha$ $\quad \sigma_{\text{hit}} = \sqrt{\text{RMS}^2_{\text{trunc.}} - \sigma^2_{\text{tel}}}$

→ as function of angle, temperature, ϕ_{eq}, V_{bias}

Setup:
- **tracking:** six Mimosa26 MAPS
- **trigger:** two upstream scintillators
- **timing:** reference module RD53B_CMS (50x50 μm²)
- **DUT** located after the first three planes





Inhomogeneously irradiated modules

Two modules irradiated at CERN PS → non-uniform fluence across columns

- Fluence range: $\phi_{\mathrm{eq}} = 3 \times 10^{15}\ \mathrm{n_{eq}cm^{-2}} \rightarrow 1 \times 10^{16}\ \mathrm{n_{eq}cm^{-2}}$

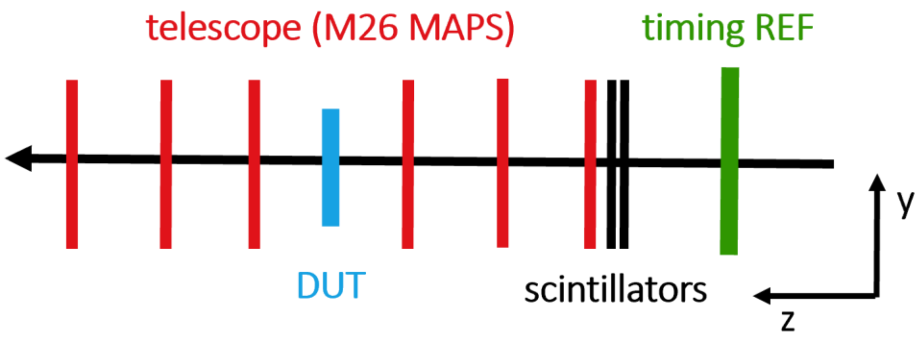
Aim: study $\varepsilon_{\mathrm{hit}}$, α, $\varepsilon_{\mathrm{hit}} \times \alpha$ and σ_{hit} as a function of the equivalent fluence ϕ_{eq}

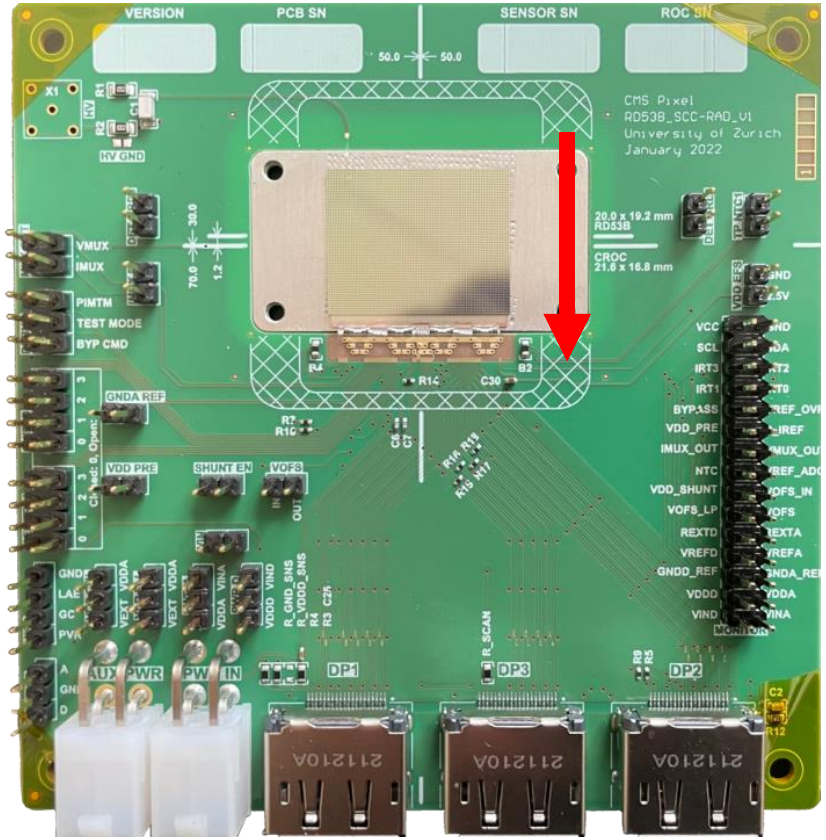
Types of **measurements**:

→ **bias scan**: fixed angle wrt. beam, threshold | change **bias voltage**
→ **angle scan**: fixed bias voltage, threshold | change **angle** wrt. beam
→ **threshold scan**: fixed angle wrt. beam, bias voltage | change **threshold**

The software (*Corryvreckan*[1]) used for the analysis of test beam data:

- **aligns** all planes and fits particle **tracks** from recorded hits





[1] D. Dannheim et al., "Corryvreckan: a modular 4D track reconstruction and analysis software for test beam data", arXiv:2011.12730

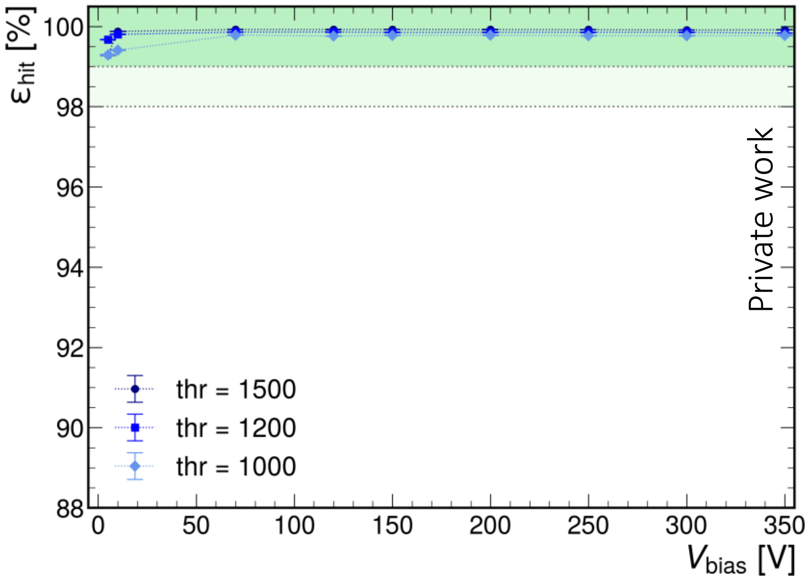
Requirements and results: ε_{hit} x α

Requirements for the **efficiency of the assembly** at vertical incidence at **-20**° C for **fresh** modules:

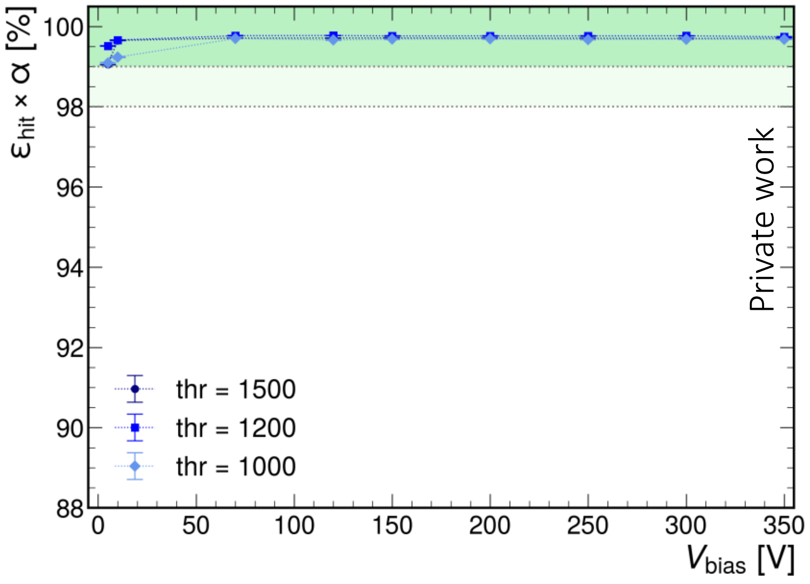
ε_{hit} x α > **99%** and V_{bias} = V_{depl} + 50 V = 120 V

< 1% masked pixels and avg. noise occupancy < 10^{-6}

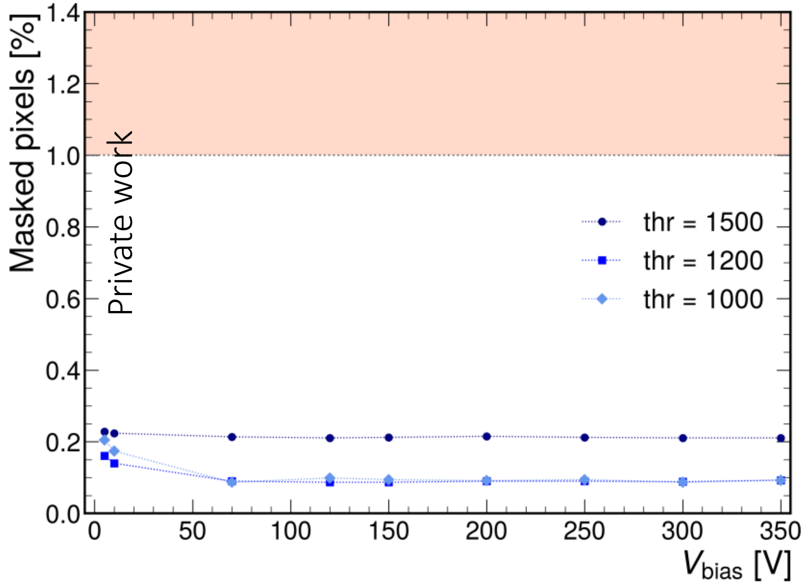
un-irradiated module



un-irradiated module



un-irradiated module



Before irradiation:

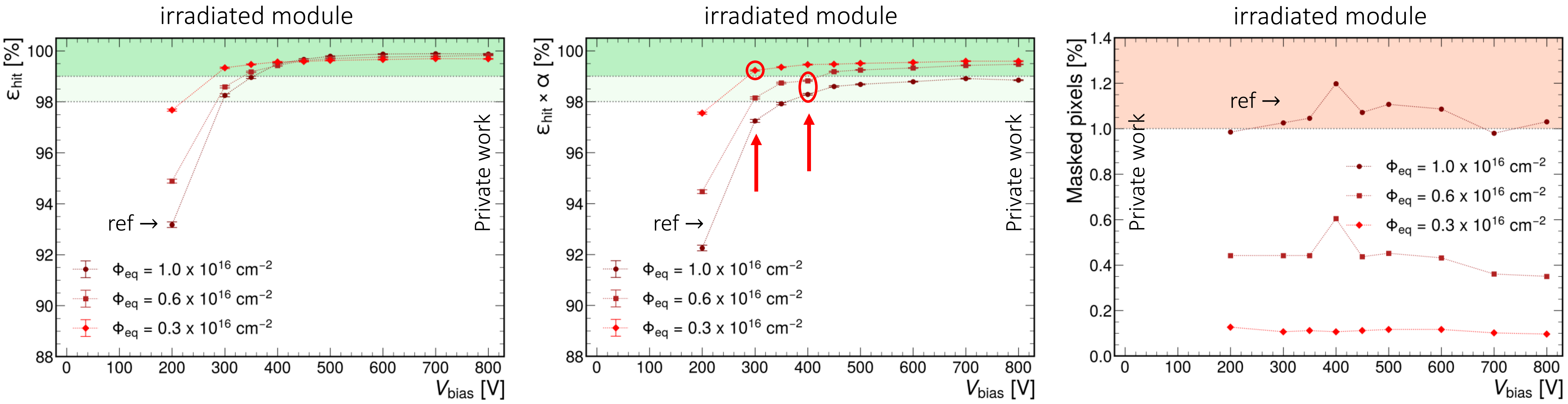
- **ε_{hit} x α > 99% for V_{bias} ≥ 0 V** for all thresholds and met requirement for masked pixels

Requirements and results: ε_{hit} x α

Requirements for the **efficiency of the assembly** at vertical incidence at -20° C for **irradiated** modules:

$$\phi_{ref} = 5\text{x}10^{15}\ \text{cm}^{-2} \rightarrow \begin{cases} \Phi_{eq} < \Phi_{ref} & \varepsilon \times \alpha > 99\% \text{ and } V_{bias} \leq 600\text{ V} \\ \Phi_{eq} > \Phi_{ref} & \varepsilon \times \alpha > 98\% \text{ and } V_{bias} \leq 800\text{ V} \end{cases}$$

< 1% masked pixels and avg. noise occupancy < 10^{-6}



After irradiation:

- plots show a section of the module tuned to a threshold = 1000 e-
- $\boldsymbol{\varepsilon_{hit}}$ **x** $\boldsymbol{\alpha}$ **> 99%** for V_{bias} ≥ 300 V and $\boldsymbol{\varepsilon_{hit}}$ **x** $\boldsymbol{\alpha}$ **> 98%** for V_{bias} ≥ 400 V and met requirement for masked pixels for $\phi_{eq} < 1 \times 10^{16}\ \mathrm{n_{eq}cm^{-2}}$

Requirements and results: $\varepsilon_{hit} \times \alpha$

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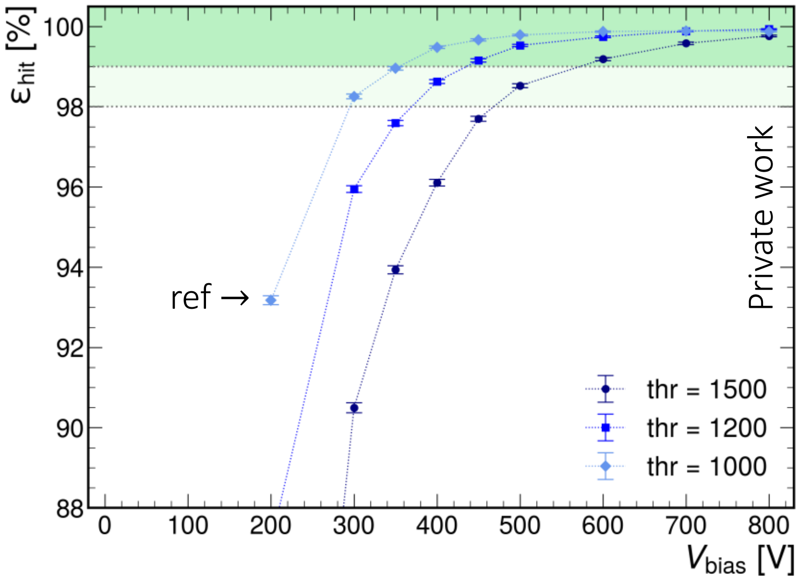
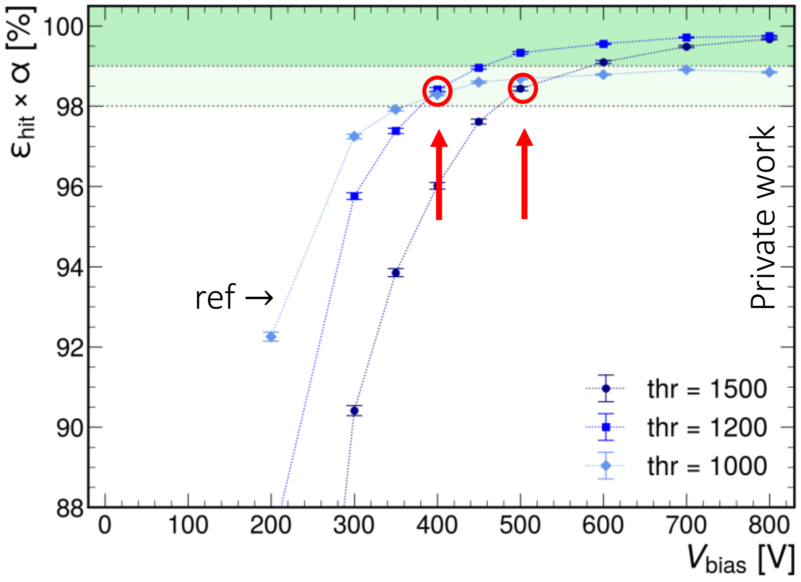
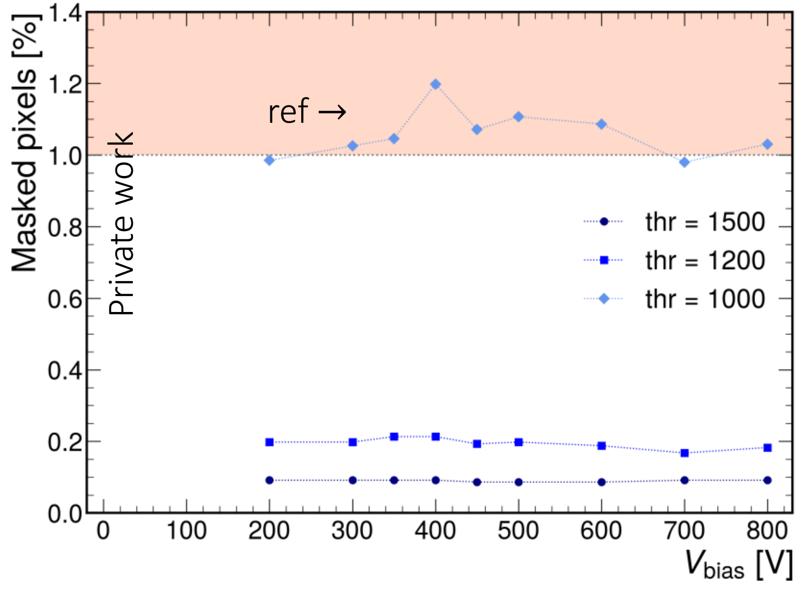
irradiated module



irradiated module



irradiated module



After irradiation:

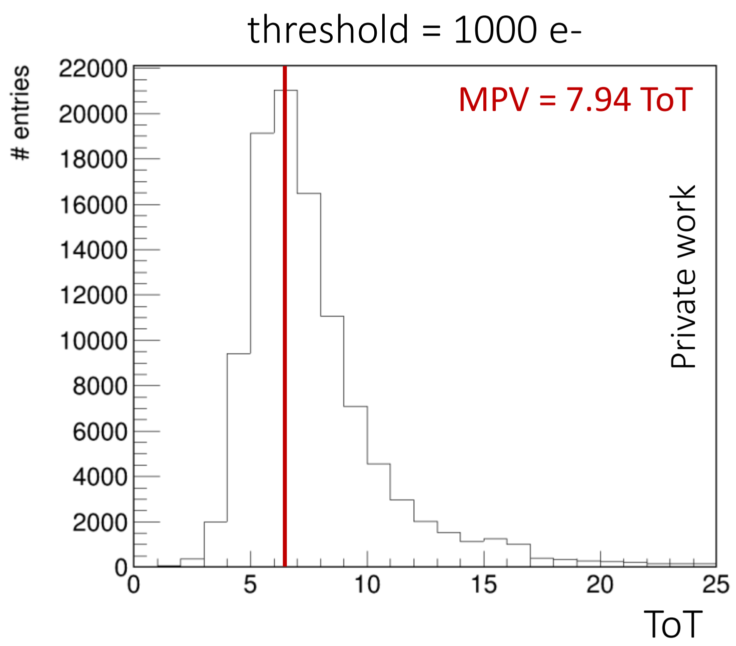
- plots show a section of the module irradiated to $\phi_{\mathrm{eq}} = 1 \times 10^{16}\ \mathrm{n_{eq}cm^{-2}}$
- $\boldsymbol{\varepsilon_{hit}}$ **x** $\boldsymbol{\alpha}$ **> 98%** for V_{bias} **≥ 400 V** (thresholds = 1000 e-, 1200 e-) and V_{bias} **≥ 500 V** (threshold =1500 e-)

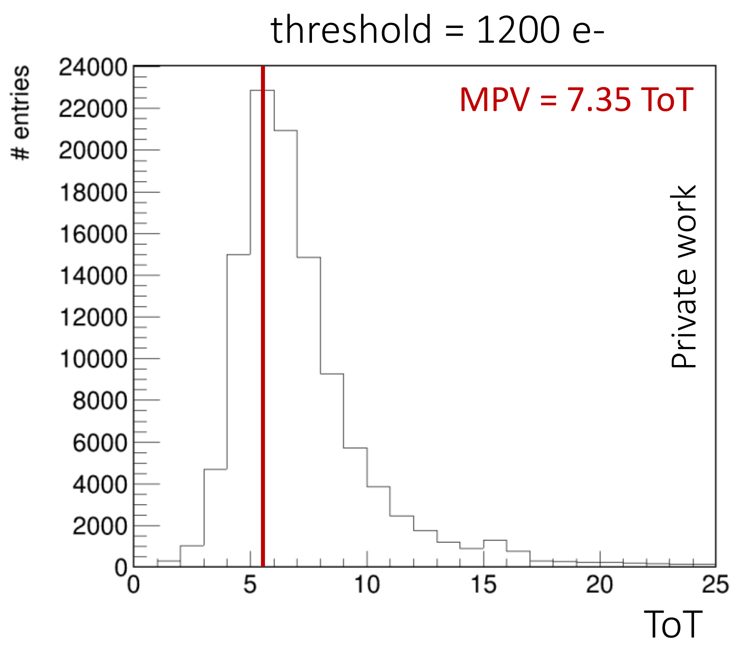
Requirements and results: ε_{hit} x α

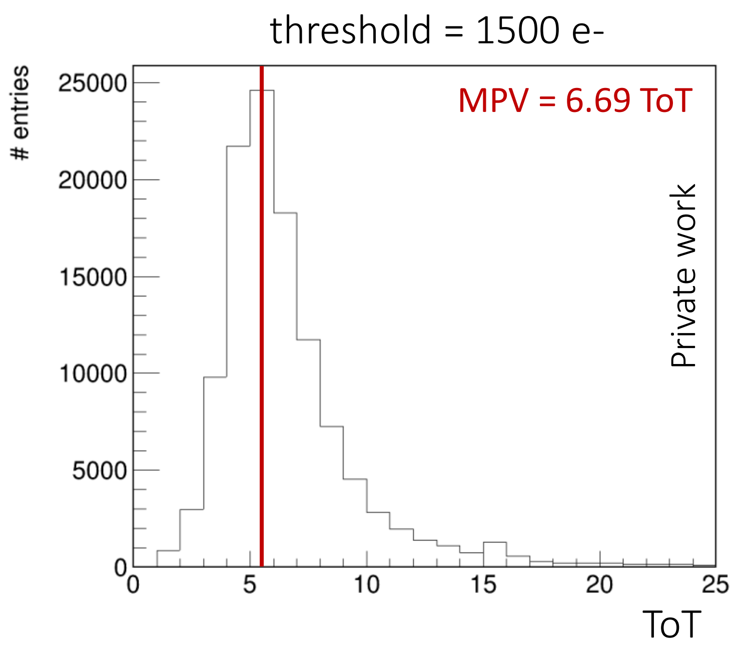
Requirements for the **efficiency of the assembly** at vertical incidence at **-20° C** for **irradiated** modules:

$$\phi_{\text{ref}} = 5\text{x}10^{15}\ \text{cm}^{-2} \rightarrow \begin{cases} \Phi_{\text{eq}} < \Phi_{\text{ref}} & \varepsilon \times \alpha > 99\% \text{ and } V_{\text{bias}} \leq 600\ \text{V} \\ \Phi_{\text{eq}} > \Phi_{\text{ref}} & \varepsilon \times \alpha > 98\% \text{ and } V_{\text{bias}} \leq 800\ \text{V} \end{cases}$$

< 1% masked pixels and avg. noise occupancy < 10^{-6}







After irradiation:

- plots show a section of the module irradiated to $\phi_{\text{eq}} = 1 \times 10^{16}\ \text{n}_{\text{eq}}\text{cm}^{-2}$
- **ε_{hit} x α > 98%** for **$V_{\text{bias}} \geq 400$ V** (thresholds = 1000 e-, 1200 e-) and **$V_{\text{bias}} \geq 500$ V** (threshold =1500 e-)

Single hit resolution σ_{hit}

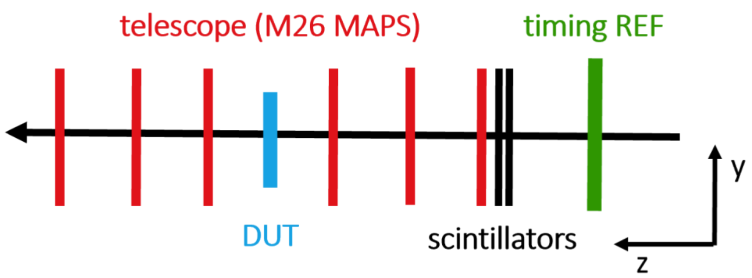
Binary limits for σ_{hit}:

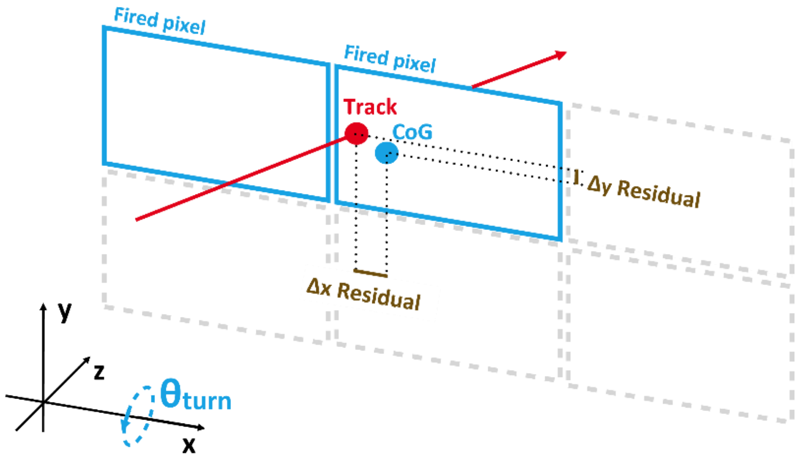
$$\begin{cases} \sigma_{hit} < 25/\sqrt{12} \sim 7.2\ \mu m \text{ in } 25\ \mu m \\ \sigma_{hit} < 100/\sqrt{12} \sim 28.9\ \mu m \text{ in } 100\ \mu m \end{cases}$$

$$\sigma_{hit} = \sqrt{RMS^2_{trunc.} - \sigma^2_{tel}}$$

$$X_{hit} = \sum_i \frac{ToT_i\, X_i}{ToT_{cluster}}$$

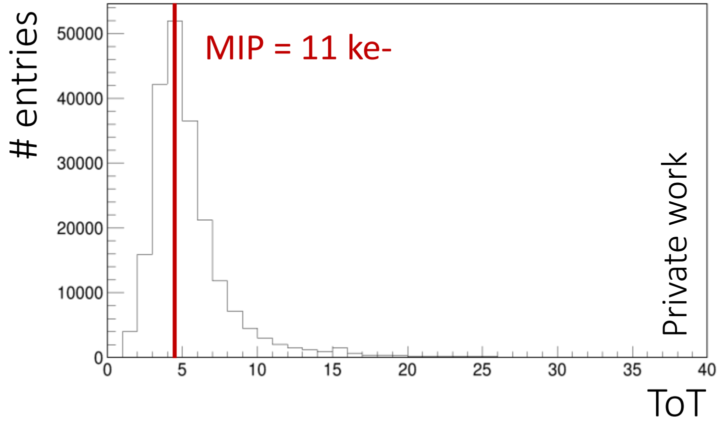
crosstalk < 10%





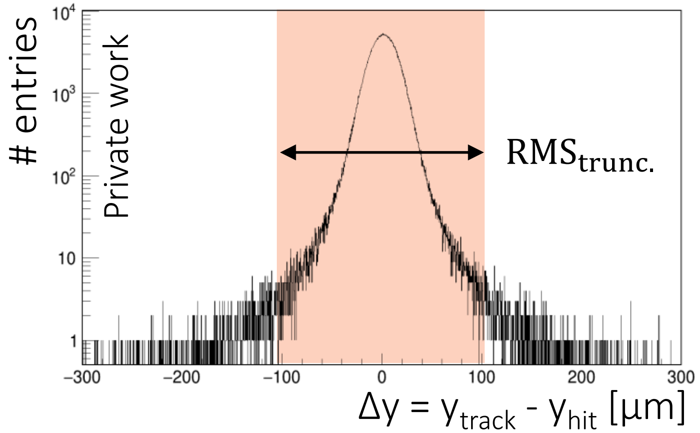
1 entry in the residuals distribution

ToT distribution

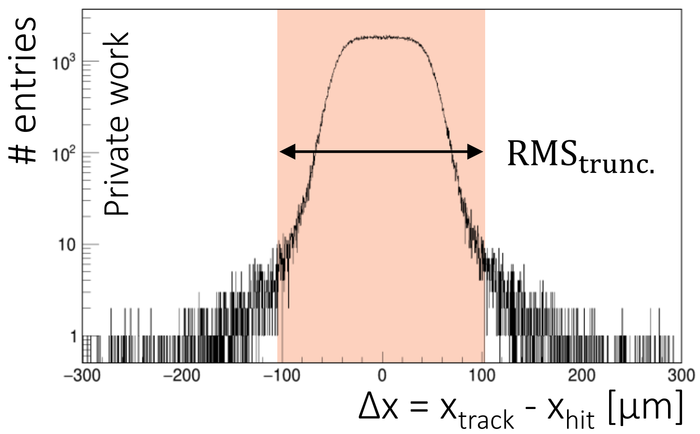


Every hit is associated to a $ToT_{cluster}$
- sum of individual ToT_i of the cluster
- weighted-mean algorithm → x_{hit}, y_{hit}

residual in local y



residual in local x



Single hit resolution σ_{hit}

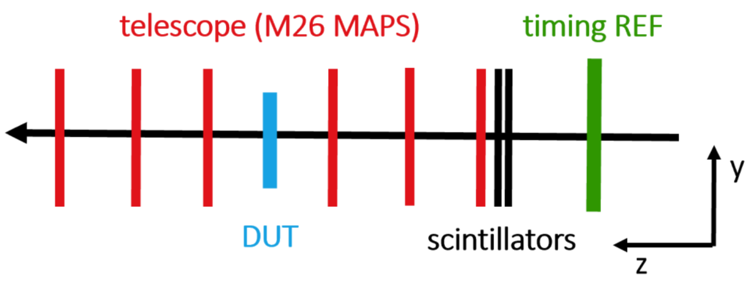
Binary limits for σ_{hit}:

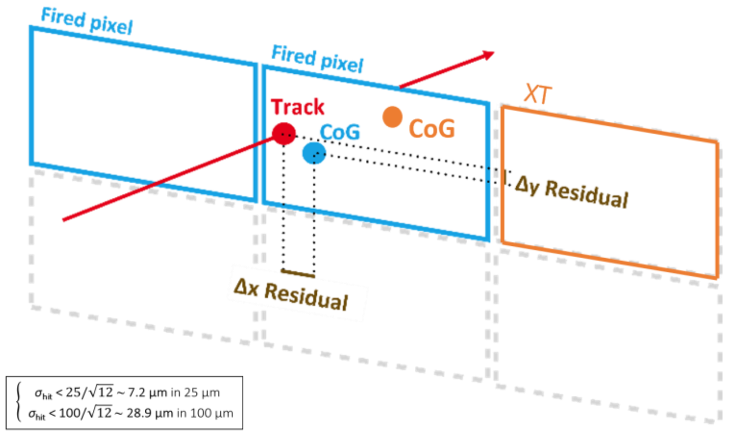
$$\begin{cases} \sigma_{hit} < 25/\sqrt{12} \sim 7.2\ \mu m \text{ in } 25\ \mu m \\ \sigma_{hit} < 100/\sqrt{12} \sim 28.9\ \mu m \text{ in } 100\ \mu m \end{cases}$$

$$\boxed{\sigma_{hit} = \sqrt{\mathrm{RMS}^2_{trunc.} - \sigma^2_{tel}}}$$

$$\boxed{X_{hit} = \sum_i \frac{\mathrm{ToT}_i\, X_i}{\mathrm{ToT}_{cluster}}}$$

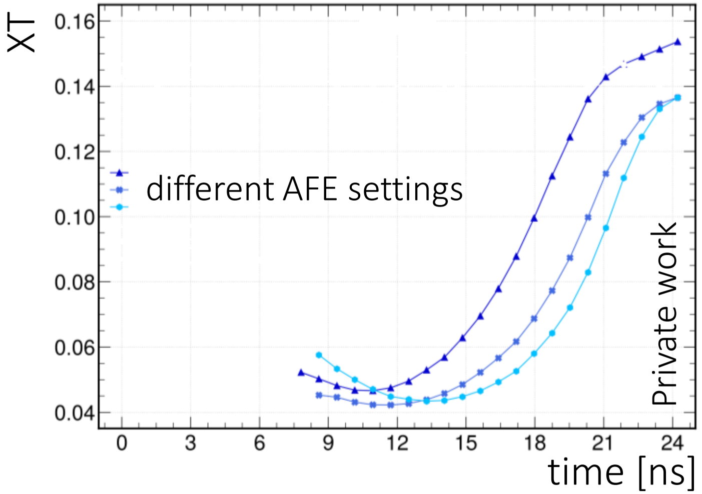
crosstalk < 10%





1 entry in the residuals distribution

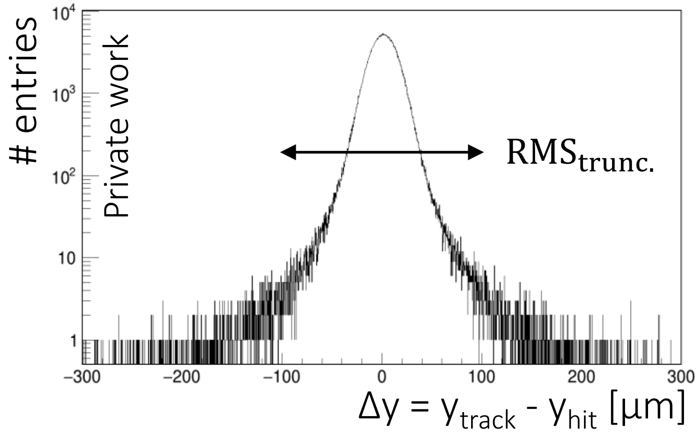
XT for RD53B_CMS



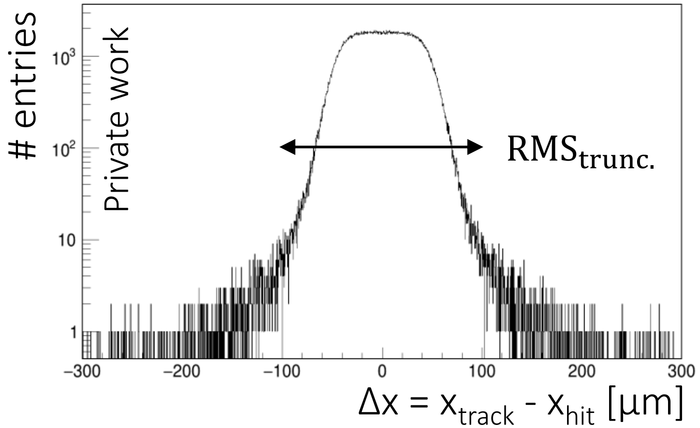
XT measured with **internal injection circuit**:

- broadens residuals distributions
- precise timing of the readout reduces XT levels to ~4%
- synchronous readout at LHC
- … more in the backup

residual in local y



residual in local x



Single hit resolution σ_{hit}

Binary limits for σ_{hit} :

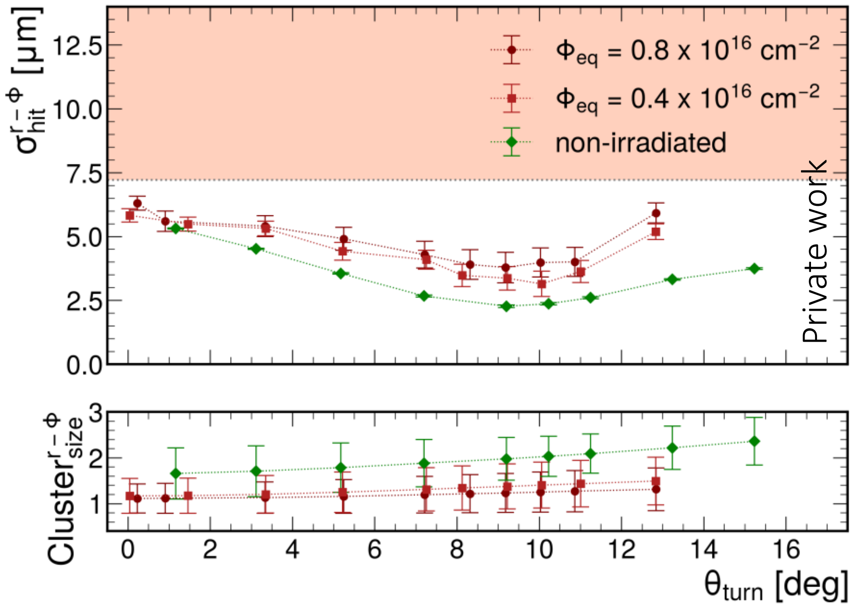
- expected minimum at optimal angle → cluster size = 2 and best charge sharing
- **25 µm** pitch corresponds to **r-ϕ** direction and **100 µm** pitch to **z**

$$\begin{cases} \sigma_{hit} < 25/\sqrt{12} \sim \mathbf{7.2\ \mu m} \text{ in 25 µm} \\ \sigma_{hit} < 100/\sqrt{12} \sim \mathbf{28.9\ \mu m} \text{ in 100 µm} \end{cases}$$

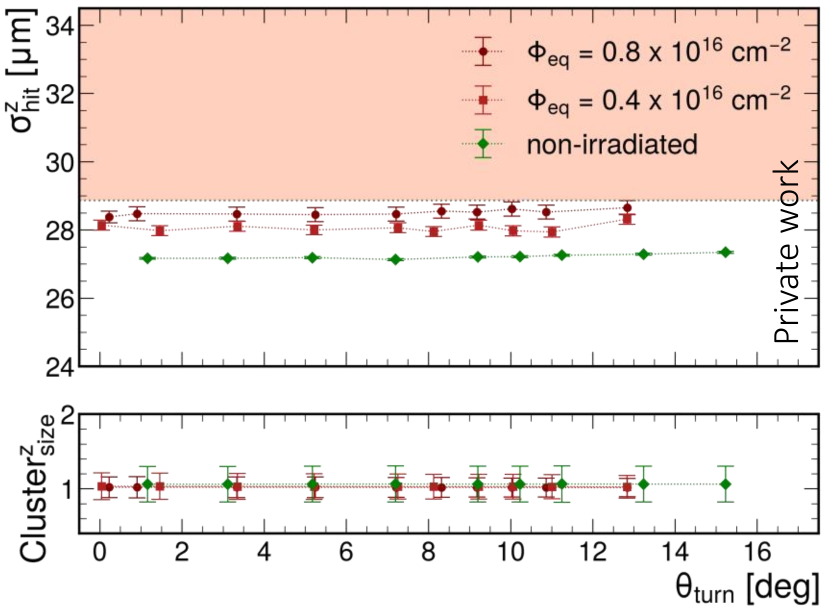
After irradiation:

- plots show a module tuned to thr = 1200 e-
- resolution below the binary limit and met requirement for masked pixels

resolution for 25 µm pitch



resolution for 100 µm pitch



Conclusions

The preliminary analysis of test beam data acquired with modules irradiated to a variety of fluences has been presented:

- all requirements concerning the $\varepsilon_{\mathrm{hit}} \times \alpha$, the σ_{hit} and the number of noisy pixels for RD53B_CMS assemblies have been met

Outlook:

- find the optimal configuration to operate the pixel assemblies throughout their lifetime at the LHC
- refine the analysis and simulate the obtained results as a function of fluence, threshold, bias voltage and incidence angle

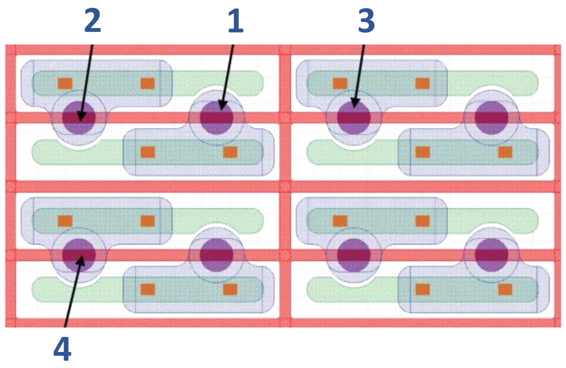
Thank you for your attention!

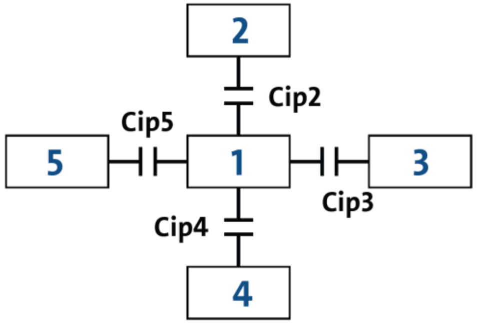
BACKUP

What is crosstalk?

When do we have crosstalk (XT)?

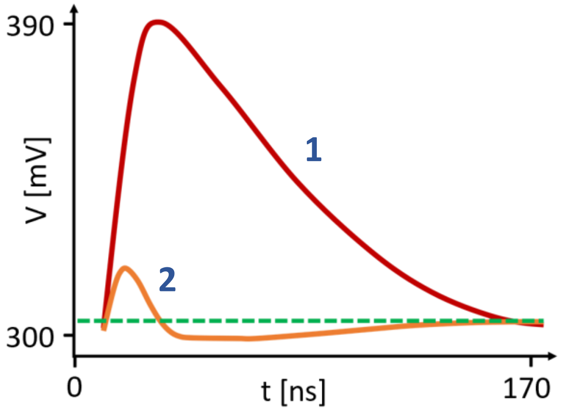
- When charge on one pixel induces a signal on a neighboring pixel → due to capacitive coupling.





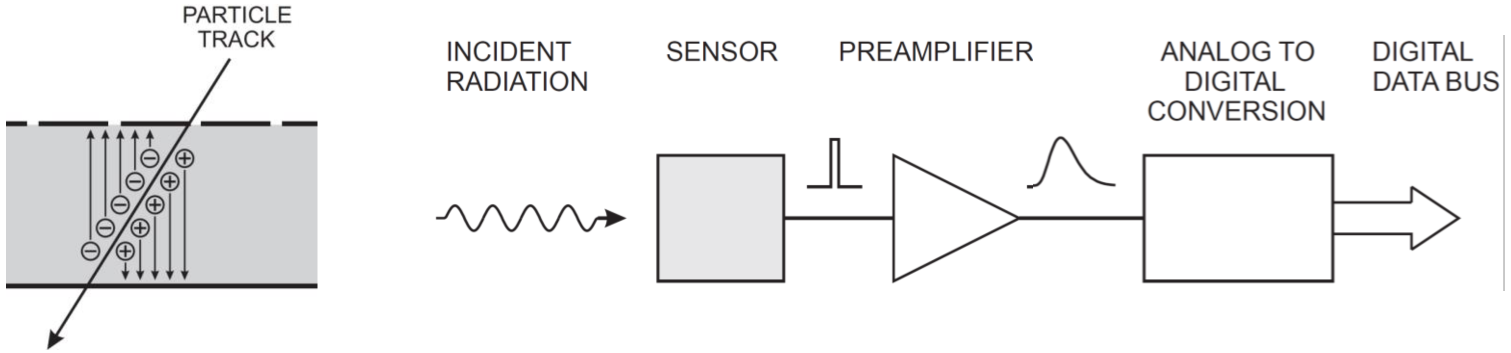
From TCAD simulations:

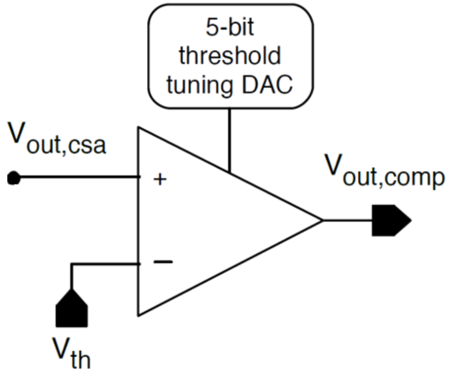
- **Values at -100 V sensor bias:**
  - **Cip2 = 14 fF**
  - **Cip4 = 6.5 fF**
  - **Cip3 = Chi5 = 2 fF**



Why do we want to get rid of it?

- XT degrades the spatial resolution biasing the position of the reconstructed hit.





$Q \propto \mathrm{ToT}$

Hit detection probability

The probability of detecting a hit is a function of:

- Injected charge Q
- Threshold of the comparator
- **Delay between injection and sampling**

Detectable charge:

- $f(\Delta t)$
- 25 ns periodicity

The **highlighted red curve**:

→ **effective threshold** of the detector

At the LHC the best timing will be chosen:

- Identifying the correct BX^0 to readout

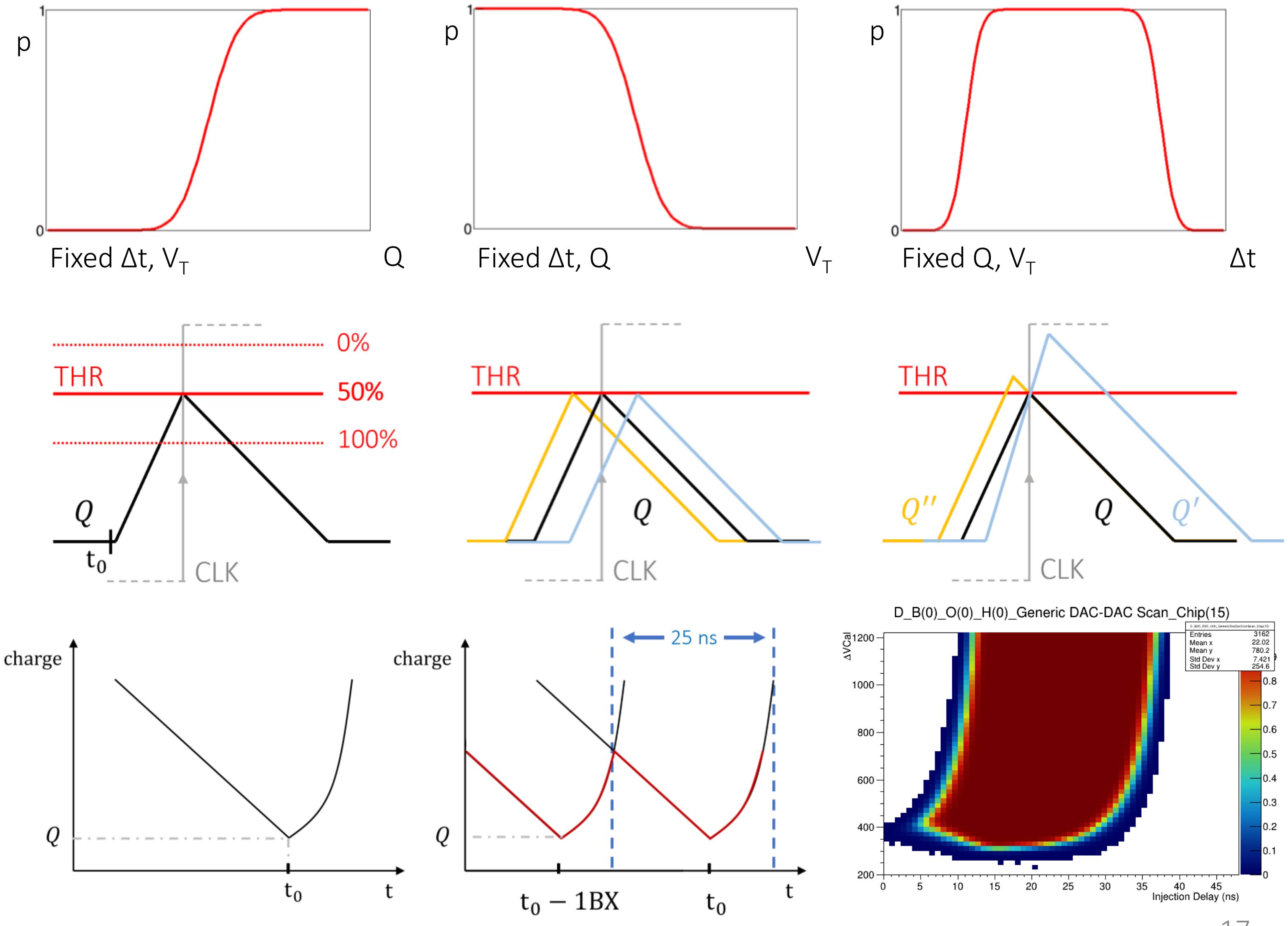
Within BX^0 and for the correct t_0 the module:

- Exhibits the highest efficiency

→ associated the lowest **threshold**

→ found for the **best delay** t_0

→ as for the **tuning procedure**

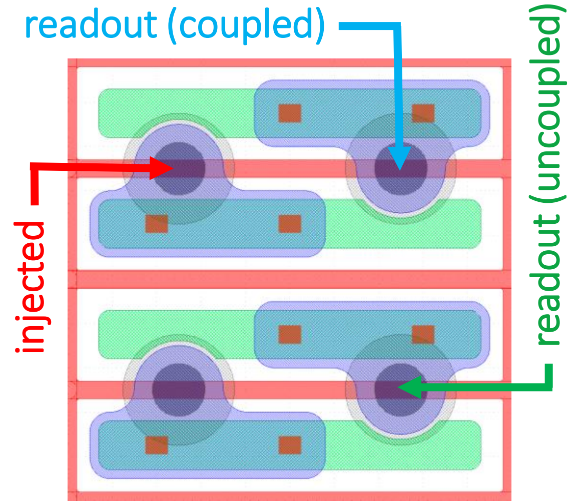


Crosstalk measurement procedure

The shape of the XT-induced signal differs from the one of the injected signal → respective thresholds can have different phase and minima

Procedure consists in changing the timing of the readout and measuring:

- Effective threshold **injected** pixel | threshold of the **coupled** pixel | threshold of the **uncoupled** pixel



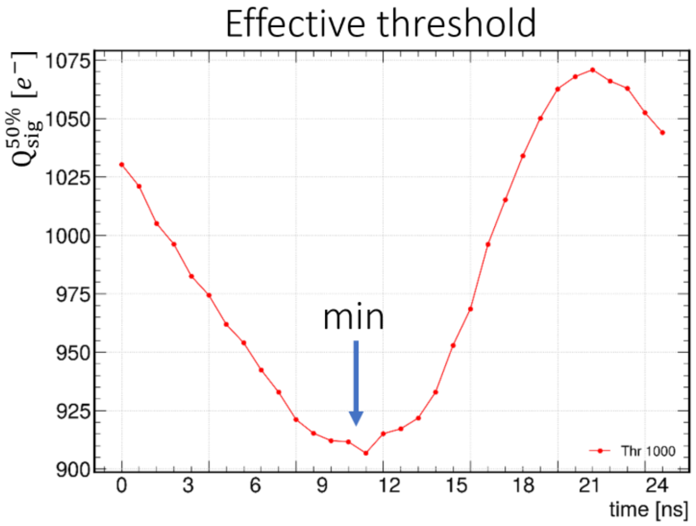
XT calculated for every fine delay:

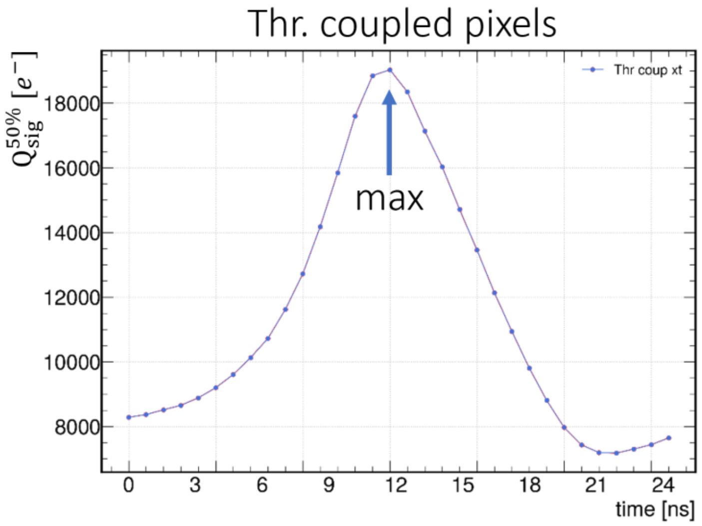
$$\mathrm{XT}_{\mathrm{un/coup}}(\mathrm{t}) = \frac{\mathrm{r}_{\mathrm{un/coup}}(\mathrm{t})}{1+\mathrm{r}_{\mathrm{un/coup}}(\mathrm{t})}$$

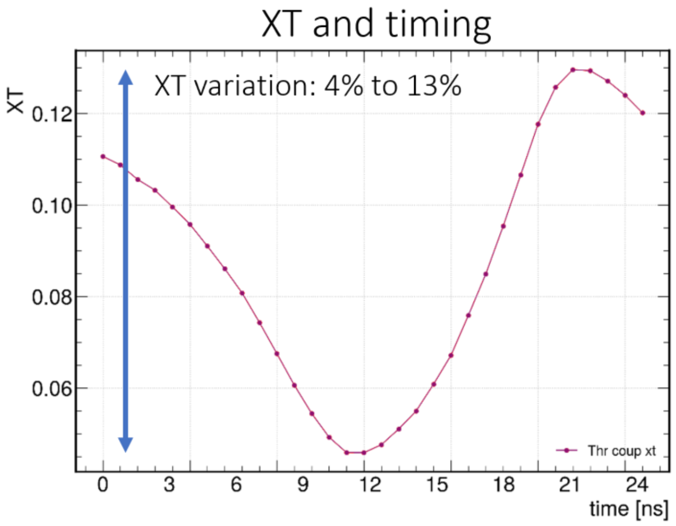
$$\mathrm{r}_{\mathrm{un/coup}}(\mathrm{t}) = \frac{\mathrm{Q}^{50\%}_{\mathrm{sig,inj}}(\mathrm{t})}{\mathrm{Q}^{50\%}_{\mathrm{sig,un/coup}}(\mathrm{t})}$$

oscillations in **anti-phase** → XT has a minimum
oscillations in **phase** → XT is stable

Anti-phase (RD53B_CMS):







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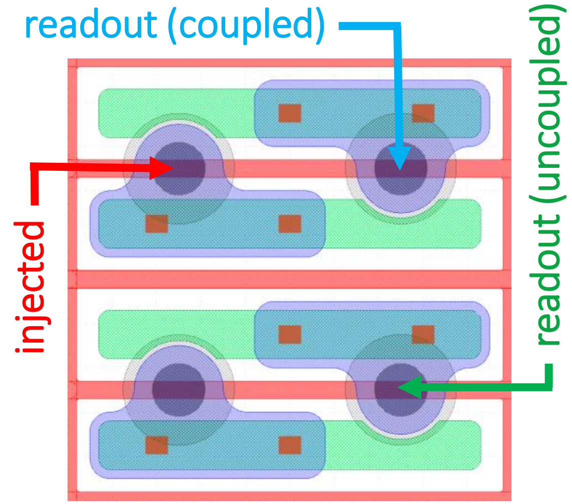


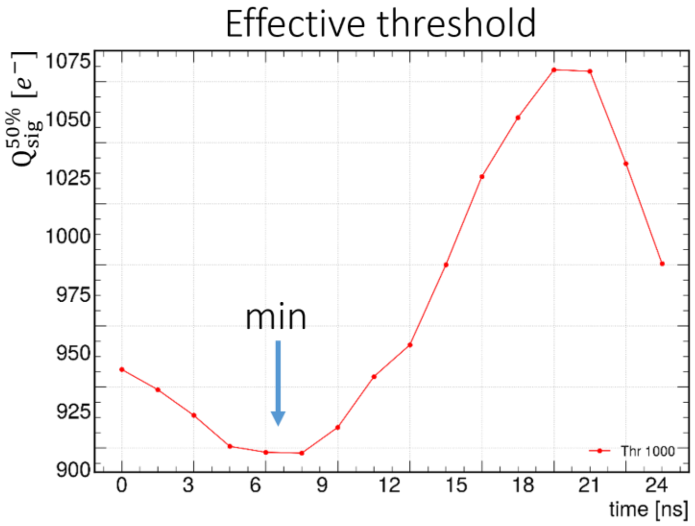
XT calculated for every fine delay:

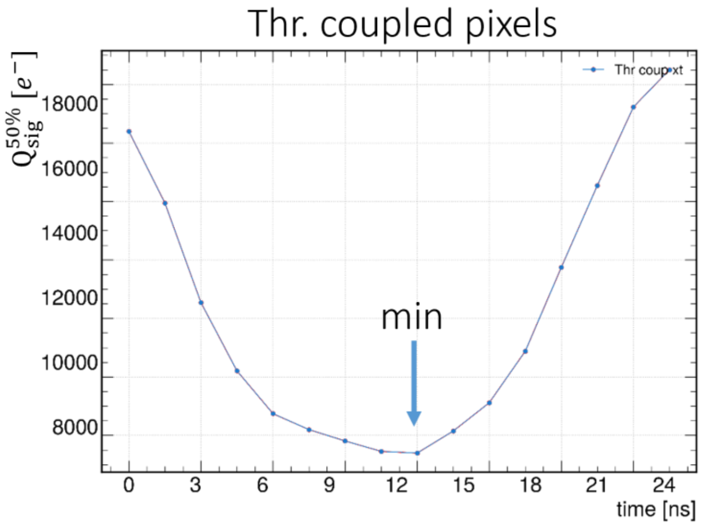
$$XT_{un/coup}(t) = \frac{r_{un/coup}(t)}{1 + r_{un/coup}(t)}$$

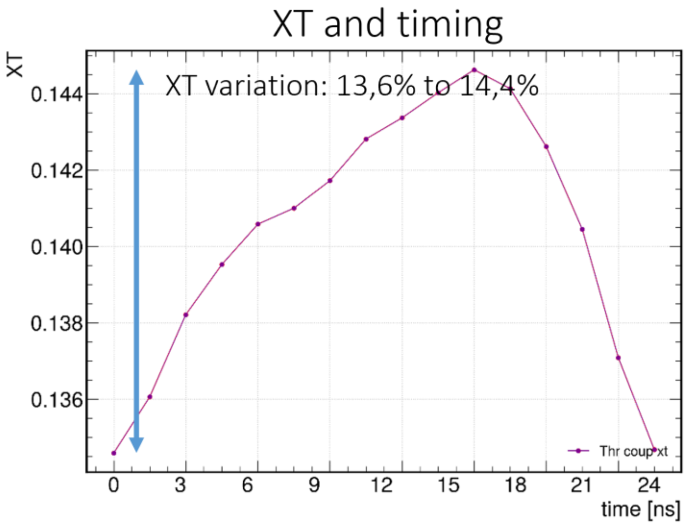
$$r_{un/coup}(t) = \frac{Q^{50\%}_{sig,inj}(t)}{Q^{50\%}_{sig,un/coup}(t)}$$

oscillations in **anti-phase** → XT has a minimum
oscillations in **phase** → XT is stable

Phase (RD53A):







Crosstalk and timing of the readout

XT was studied for CROC and RD53A assemblies with **bitten HPK 25x100** planar sensors for different:

- **pre-amp biasing** | **discharge modes**: fast, slow | **readout chips** (**RD53A** and **CROC**) → always in **synchronous** mode | reading out **1 BX**

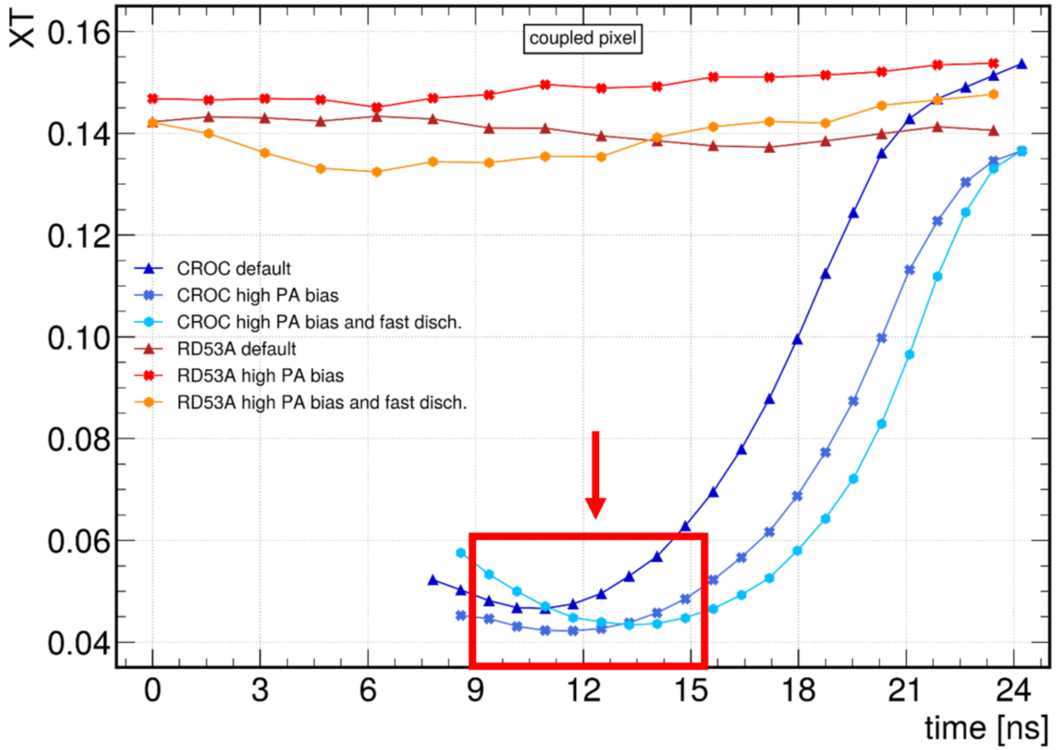
In the **region where the effective threshold is minimized**:

CROC
$$\mathrm{XT_{coup}} = 4\% - 6\%$$
$$\mathrm{XT_{uncoup}} = 2.4\% - 2.8\%$$

RD53A
$$\mathrm{XT_{coup}} = 14\%$$
$$\mathrm{XT_{uncoup}} = 4.5\%$$

crosstalk < 10%

XT and fine delay for coupled pixels



XT and fine delay for uncoupled pixels