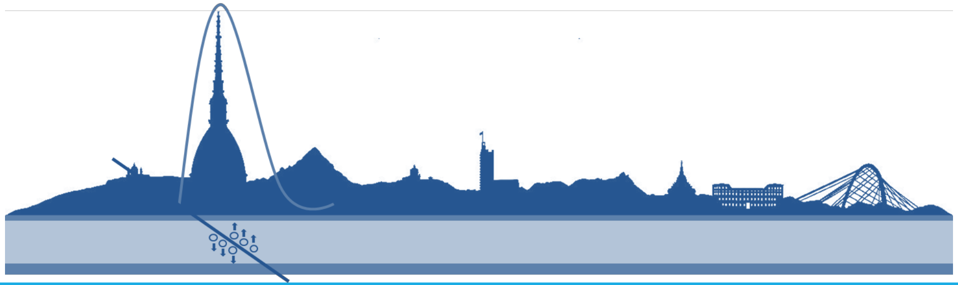
Workshop on Pico-Second Timing Detectors for Physics and Medical Applications
Torino
16-18 May 2018

Low-Gain Avalanche Diodes for Precision Timing in the CMS Endcap

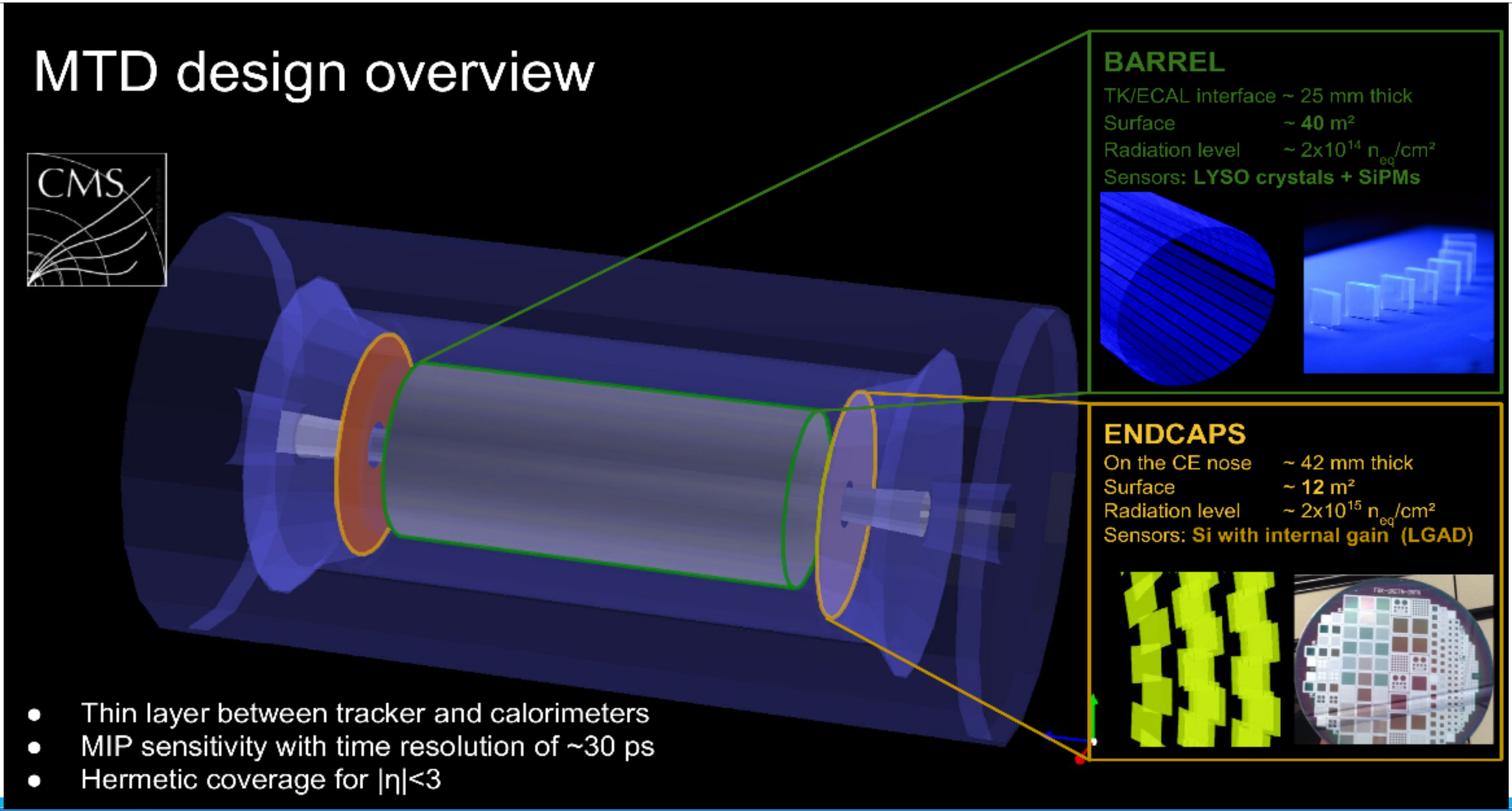
V. Sola on behalf of the CMS Collaboration



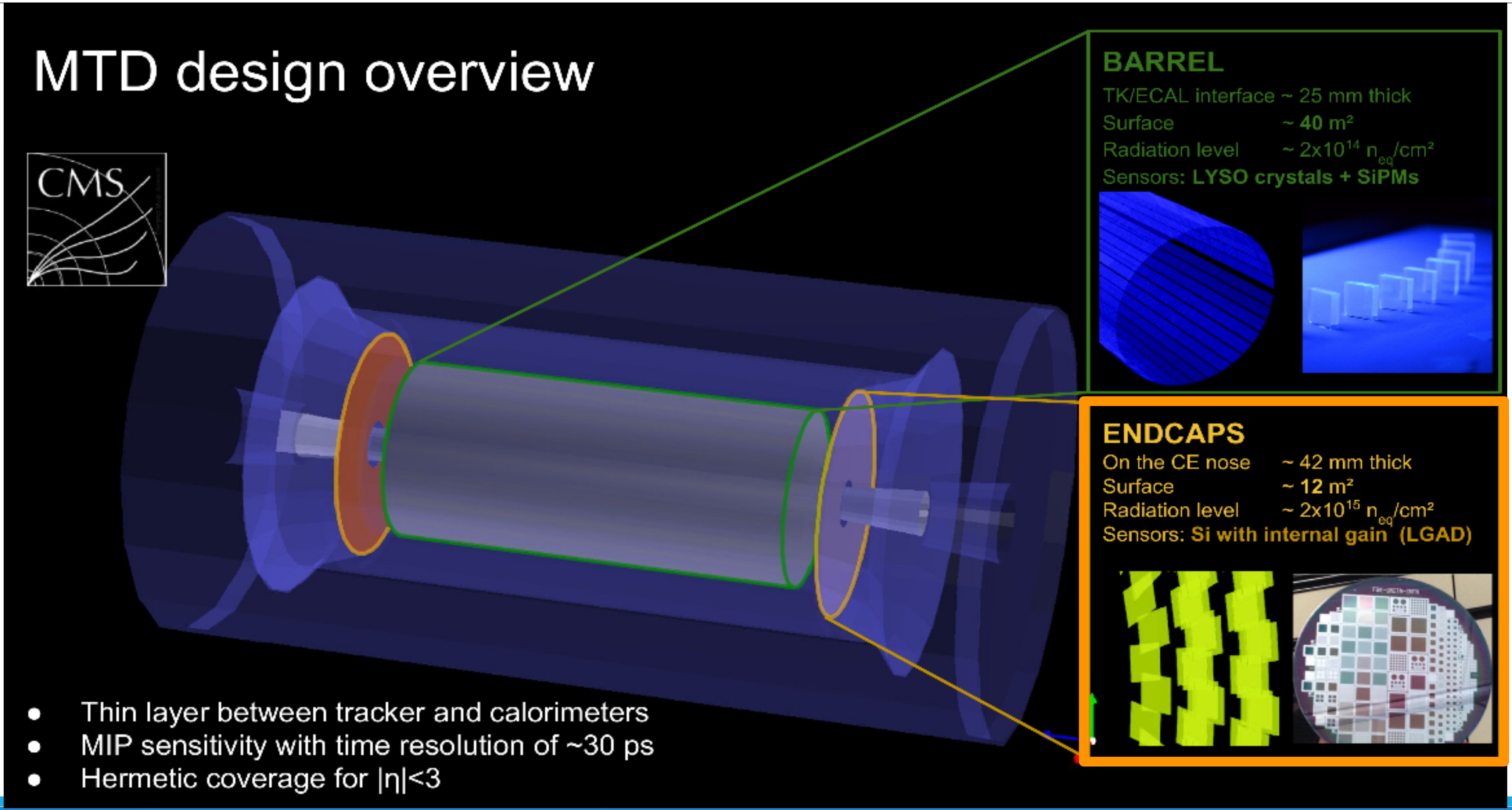
OUTLINE

- **Endcap Timing Layer overview**
- **Low-Gain Avalanche Diodes for large area detectors**
  - R&D on the production processes
  - Improvement on the radiation tolerance
- **Front-End design for fast signals**
  - ToT vs CFD
  - Effects of radiation on signal shape
- **Clock distribution**

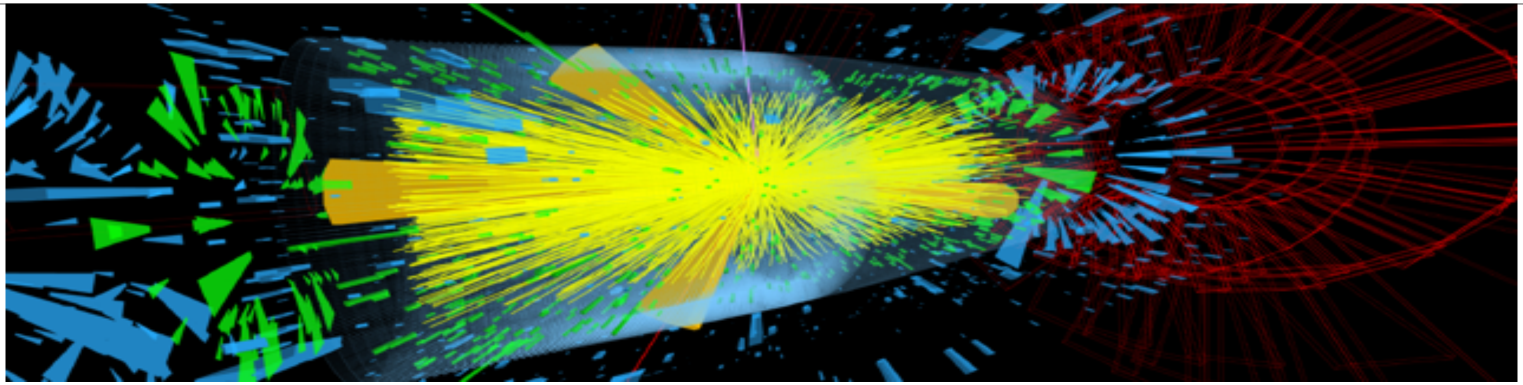
MIP Timing Detector for CMS Phase II Upgrade



MIP Timing Detector for CMS Phase II Upgrade

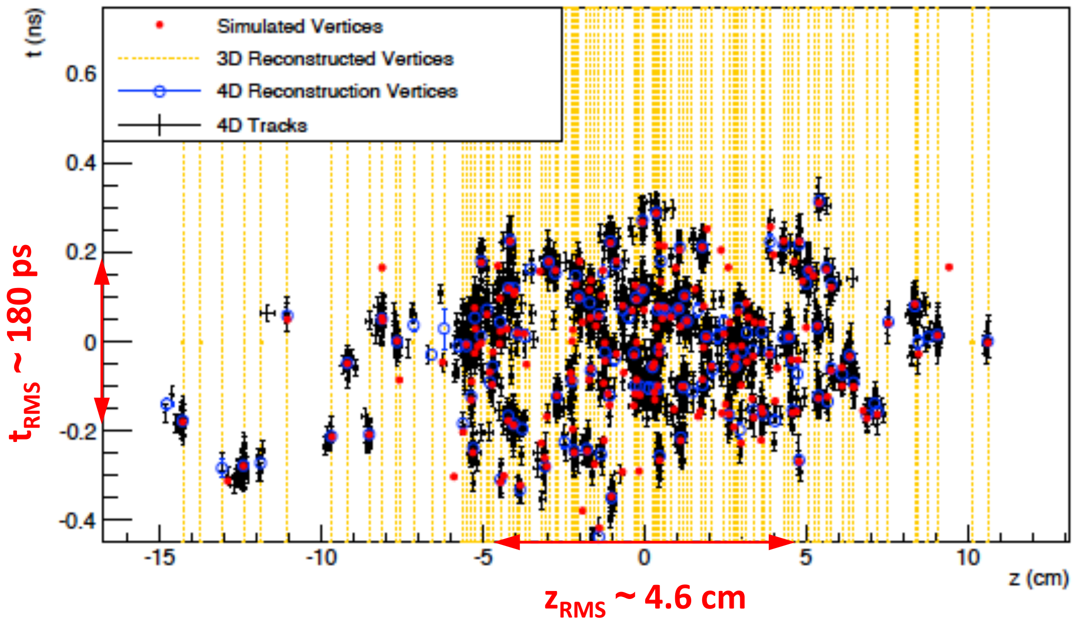


Why an Hermetic MTD?



Simulation of a
VBF H → ττ
in 200 pile-up
pp collisions

200 pp vertices



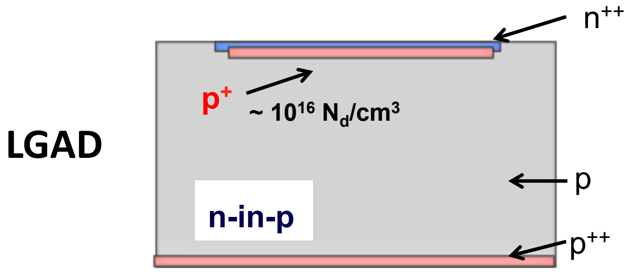
The addition of track-time information with 30 ps resolution reduces the wrong track-to-vertex associations to a level comparable to the current LHC running conditions

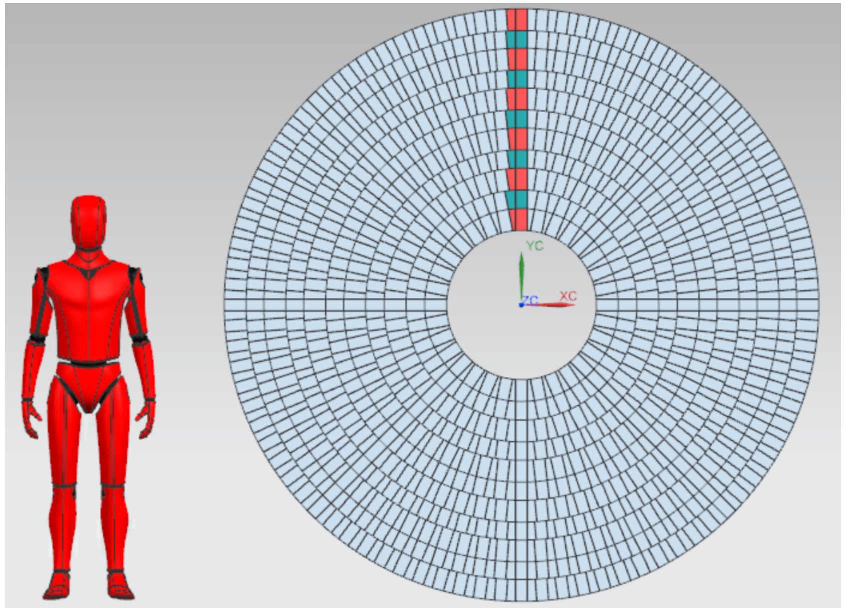
☞ **Vertex merging is reduced from 15% in space to 1% in space-time**

Endcap Timing Layer - ETL

	Barrel LYSO+SiPM	Endcap LGAD
Coverage	$\|\eta\| < 1.5$	$1.5 < \|\eta\| < 3.0$
Surface Area	$\sim$ 40 m^2	$\sim$ 12 m^2
Power Budget	$\sim$0.5 kW/m^2	$\sim$1.8 kW/m^2
Radiation Dose	$\leq$ 2e14 neq/cm^2	$\leq$ 2e15 neq/cm^2
Installation Date	2022	2024

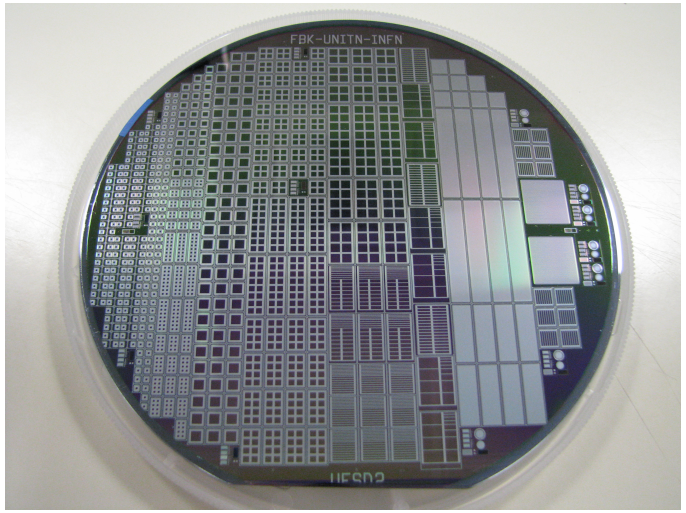
- Low-Gain Avalanche Diodes (LGAD) operated with gain $\mathcal{O}(10)$ for sufficient S/N
- Small pixel area to cope with the high occupancy at high η values
- High radiation tolerance up to ~ $3 \cdot 10^{15}$ n_{eq}/cm^2
- Installation date allows for some R&D

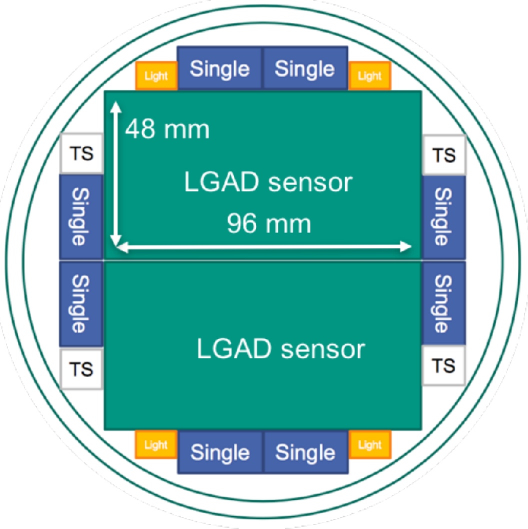


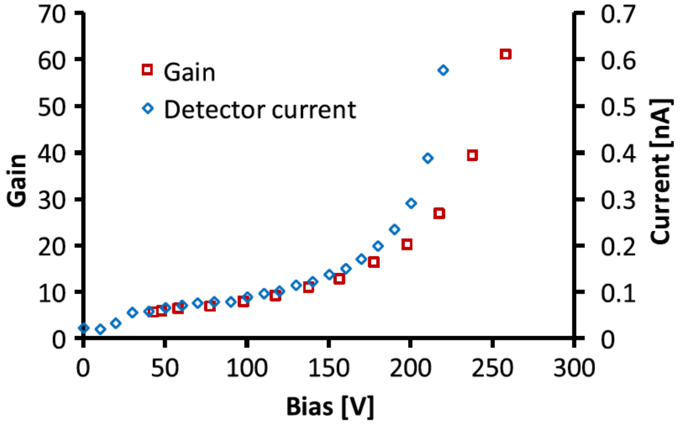


- Overlapping disk structure for hermetic coverage with single LGAD layer ~ 95% coverage, driven by inactive region between pixels
- 1x3 mm^2 LGAD pixels, read out in groups of 3 for $|\eta| < 2.1$, where occupancy allows
- 1.8 M channels at read-out level

LGAD from **mm²** to **m²**



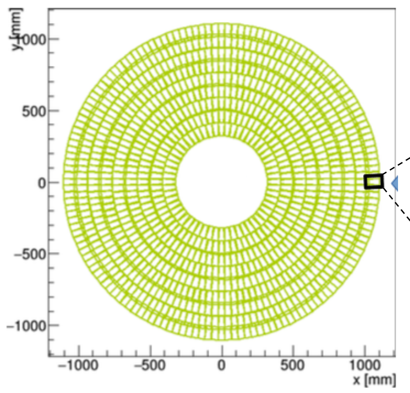


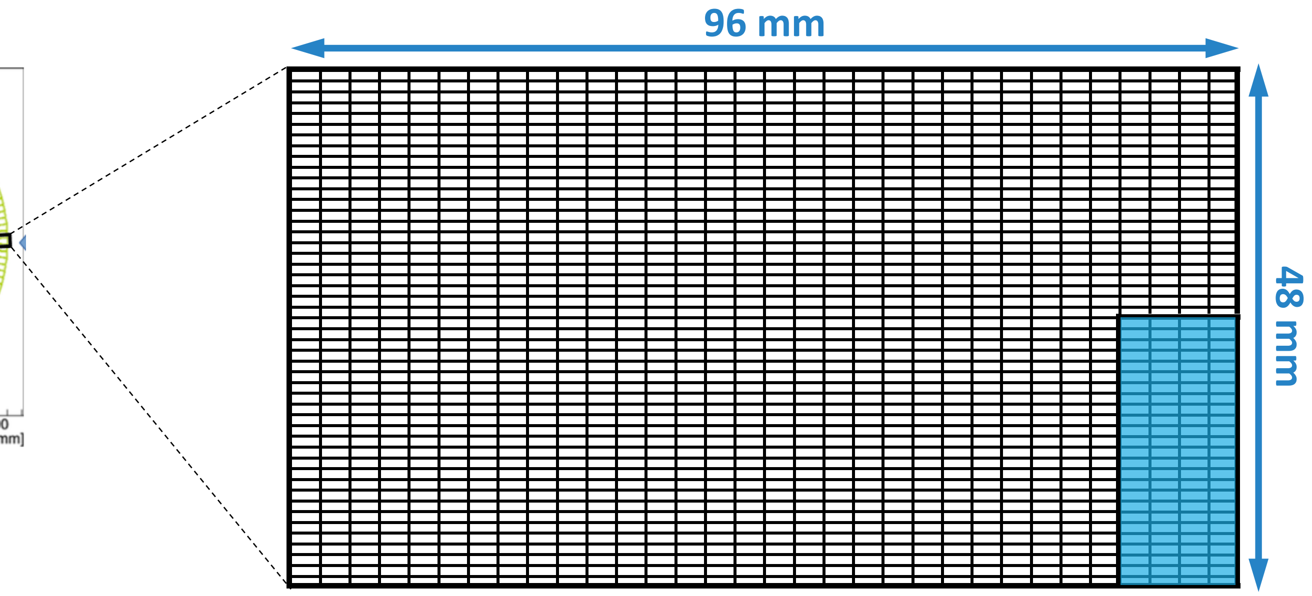


[N. Cartiglia et al., NIM A 850 (2017) 83-88]

- LGAD are routinely produced by 3 vendors (CNM, FBK, HPK)
- The time resolution of thin (~ 50 μm) LGAD is 30-35 ps
- The low gain allows segmenting and keeping the shot noise small, below the electronic noise, since the dark current is low
- **A very clean production process is necessary to keep the detector noise low, as the sensor dark current is multiplied by the gain mechanism**

Sensor Strategy





- **The 3 vendors plan to produce first demonstrators of big LGAD sensors in 2018**
  First test sensor is made of 24x4 pads - 1/16 of the full ETL sensor → **1 read-out chip size**

⇒ **First time that big sensors with internal gain are produced**

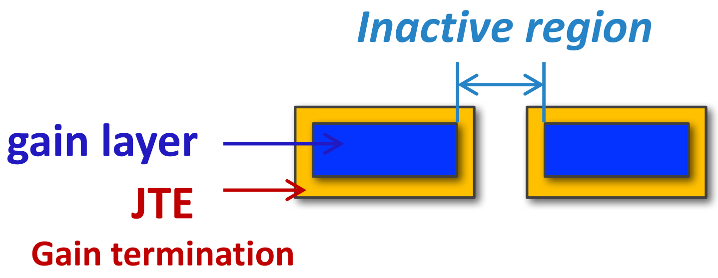
Final Goal:

- Produce 2624 sensors → **1400 6-inch wafers**
- Each sensor is **48x96 mm²** with **1536 pads**,
  each pad is **1x3 mm²**

Crucial Aspects:

- **Sensor size**
- **Fill factor**
- **Radiation tolerance**

Fill Factor Status

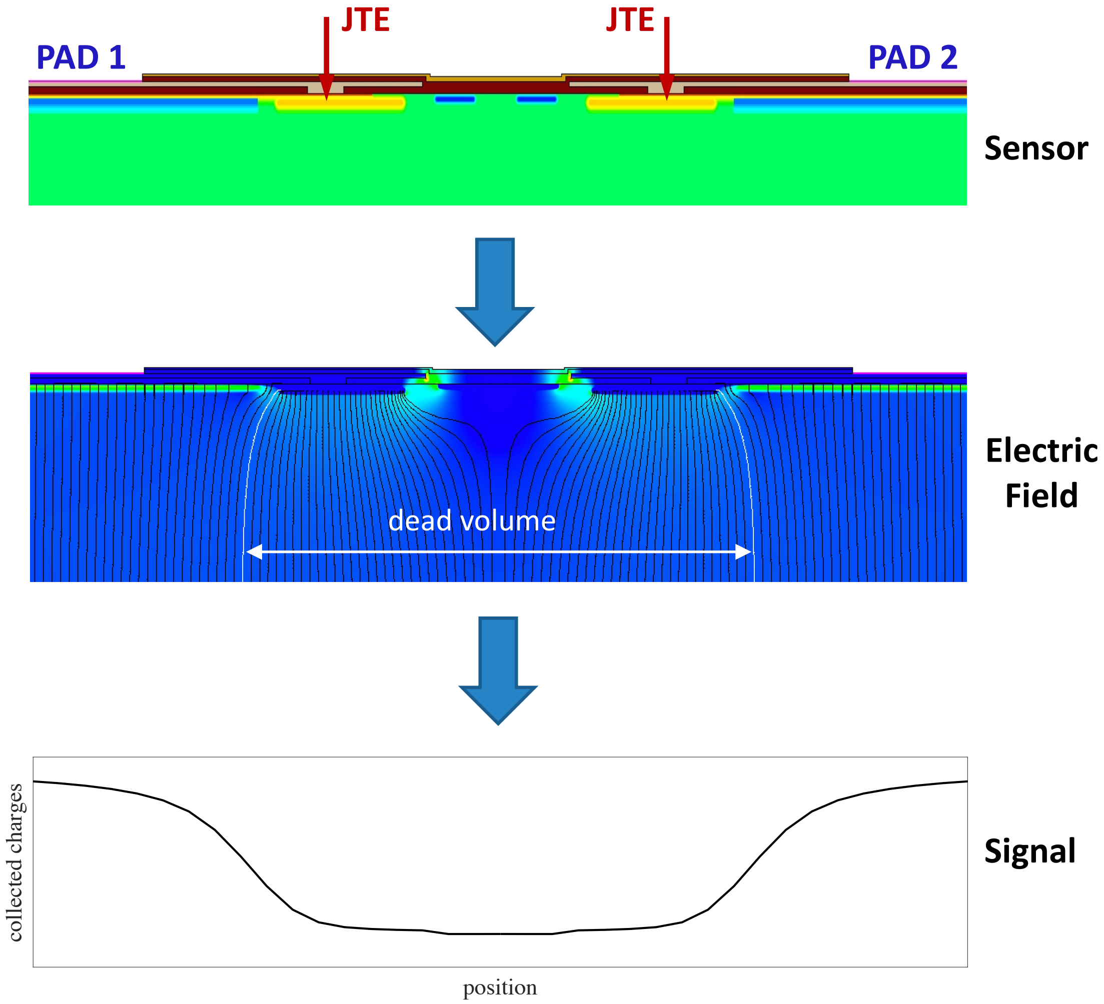


Fill Factor = Active Area / Geometrical Area

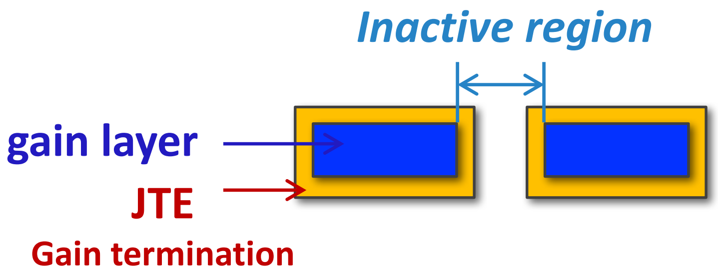
The fill factor is mainly determined by the inactive gap between sensors

Current measured gap size:
- ~ 70 μm for CNM
- ~ 70 μm for FBK
- ~ 100 μm for HPK

70 μm gap corresponds to a 91% fill factor



Fill Factor Plans



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Current measured gap size:

- ~ 70 μm for CNM
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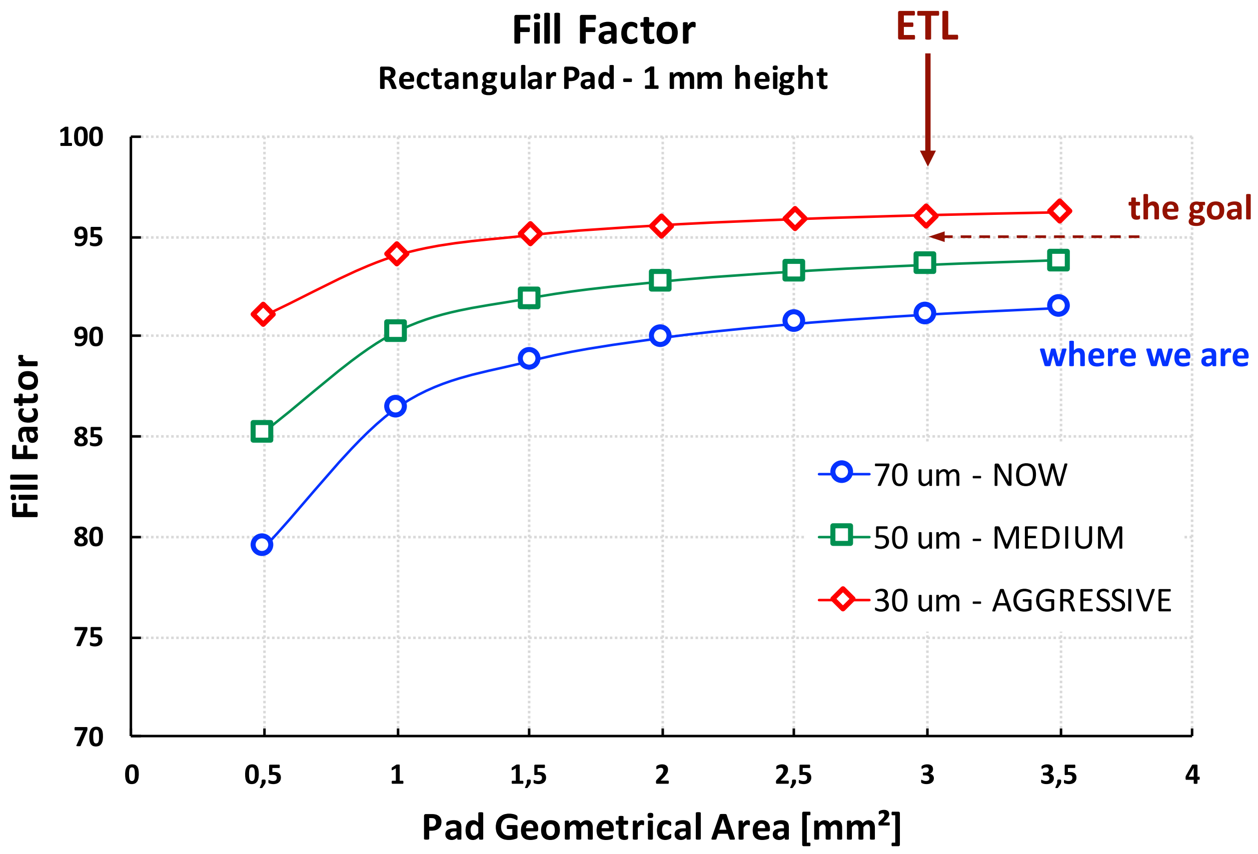
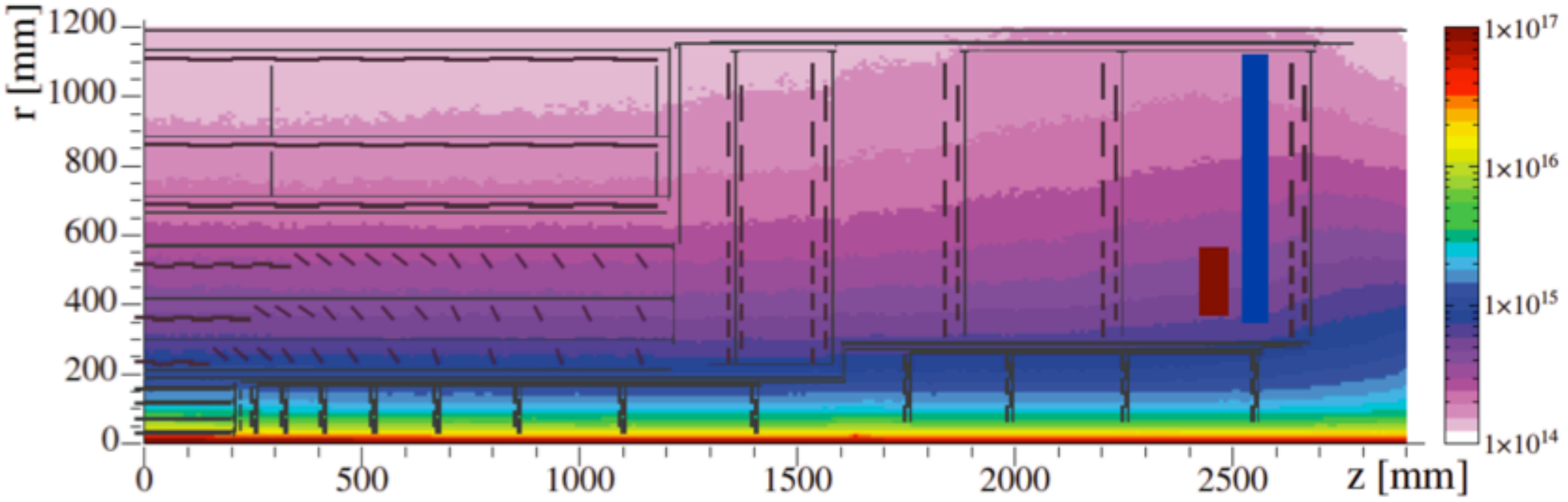
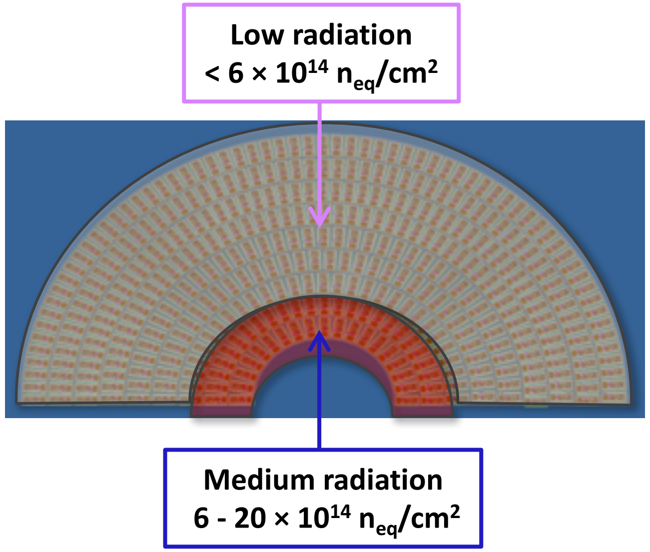
70 μm gap corresponds to a 91% fill factor

→ **30 μm gap corresponds to 96% fill factor CNM, FBK, HPK are working towards this result**



Expected Radiation for ETL Life Time





LGAD reach 35 ps time resolution for fluences up to 5 - 6 × 10^{14} n_{eq}/cm^2

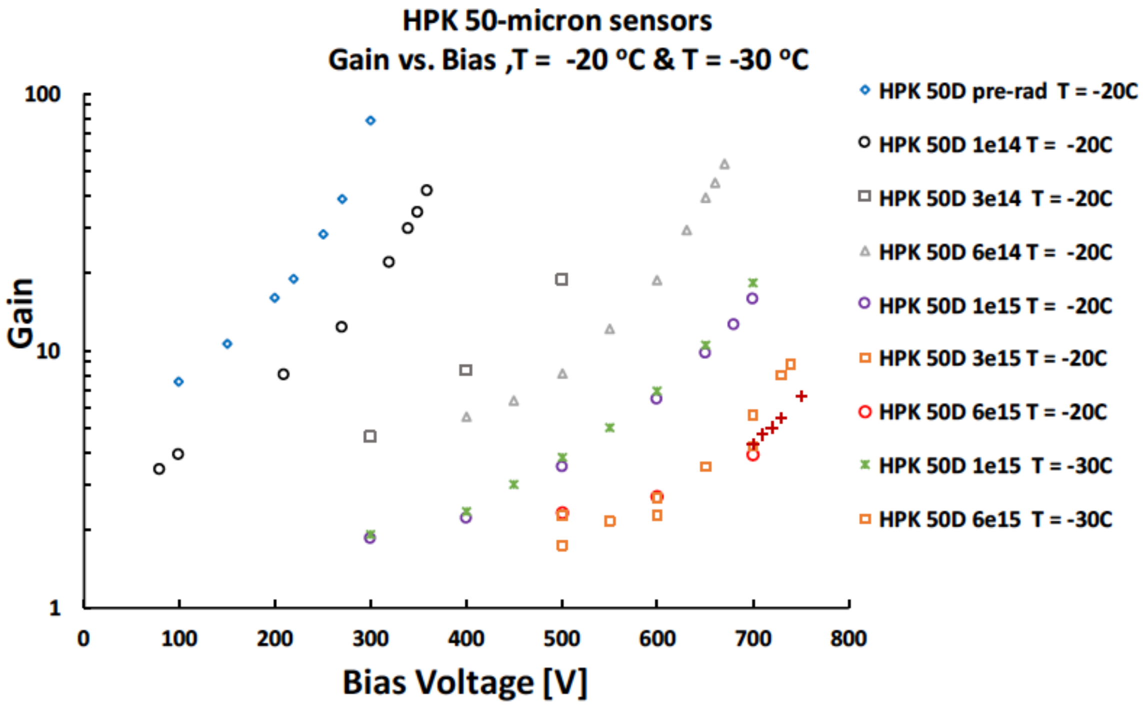
Low radiation: radius 50 - 130 cm → 4.8 m^2, ~ 90%
Medium radiation: radius 30 - 50 cm → 0.5 m^2, ~ 10%

⇒ **LGAD guarantee unchanged running conditions for > 90% of the ETL coverage**

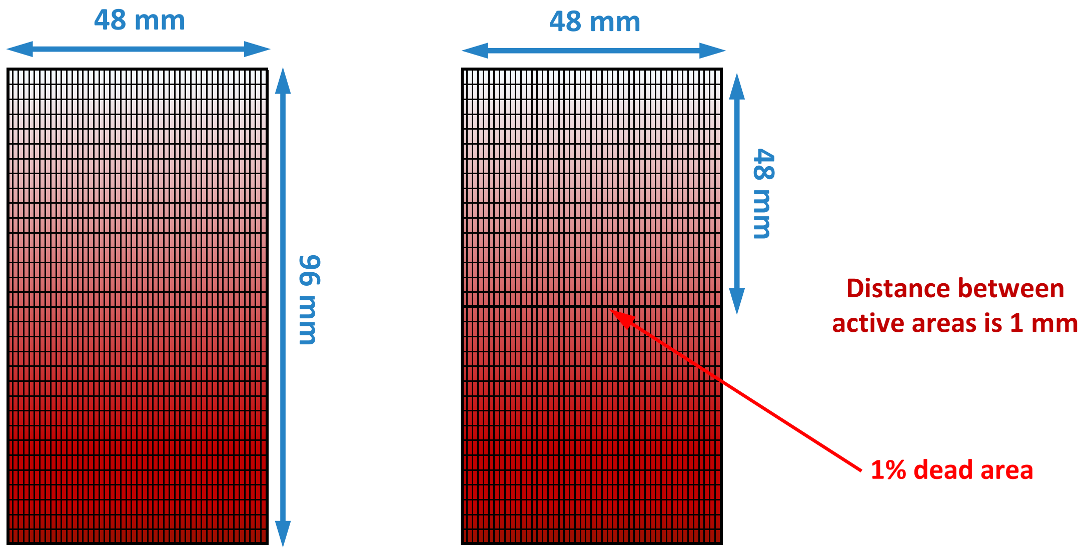
- **For the remaining 10%, higher bias values will compensate for the gain reduction**
- **Carbon doped gain layer mitigates the Boron deactivation inside the gain layer volume**

Radiation Effects on Boron-Doped LGAD

- ➢ Irradiation decreases the gain layer active doping → less gain
- ➢ Increase bias to compensate gain loss → recover good time resolution



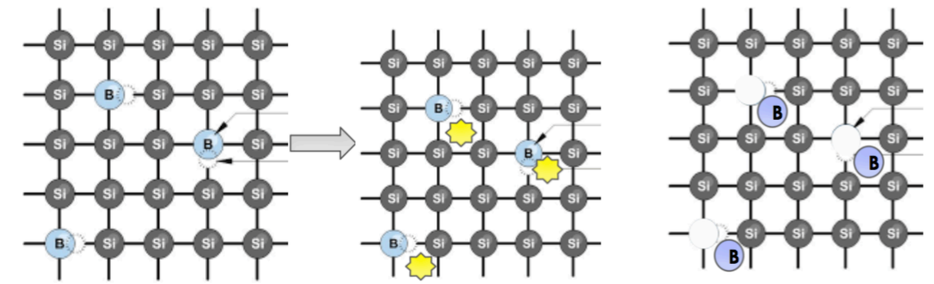
[Z. Galloway et al., arXiv:1707.04961]



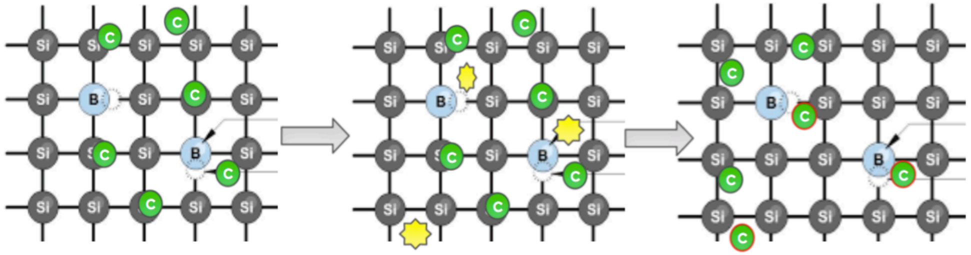
- ➢ **Splitting the sensors in 2 parts mitigates the gain reduction due to irradiation but reduces the fill factor**

Radiation Effects on Boron+Carbon UFSD

- ➢ Adding Carbon to the Boron implant **halves** the reduction of the gain layer doping due to irradiation

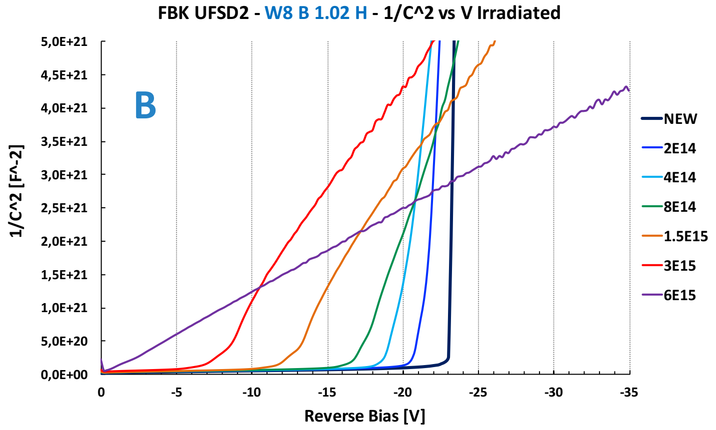


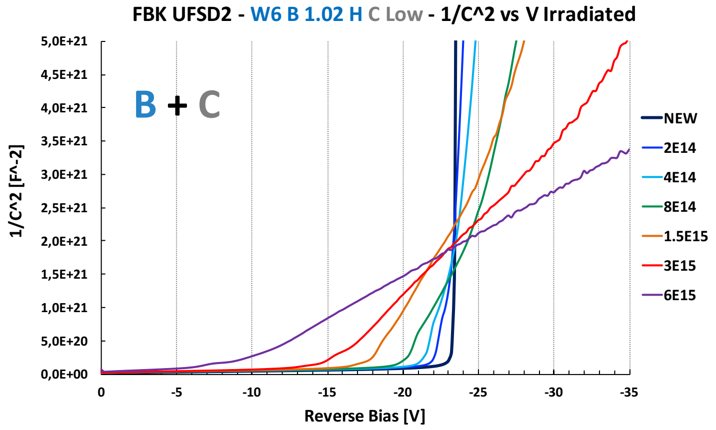
Boron
Radiation creates interstitial defects that inactivate the Boron



Carbon
Interstitial defects filled with Carbon instead of with Boron and Gallium

$1/C^2$ vs V_{bias} give information on the doping density inside the silicon volume

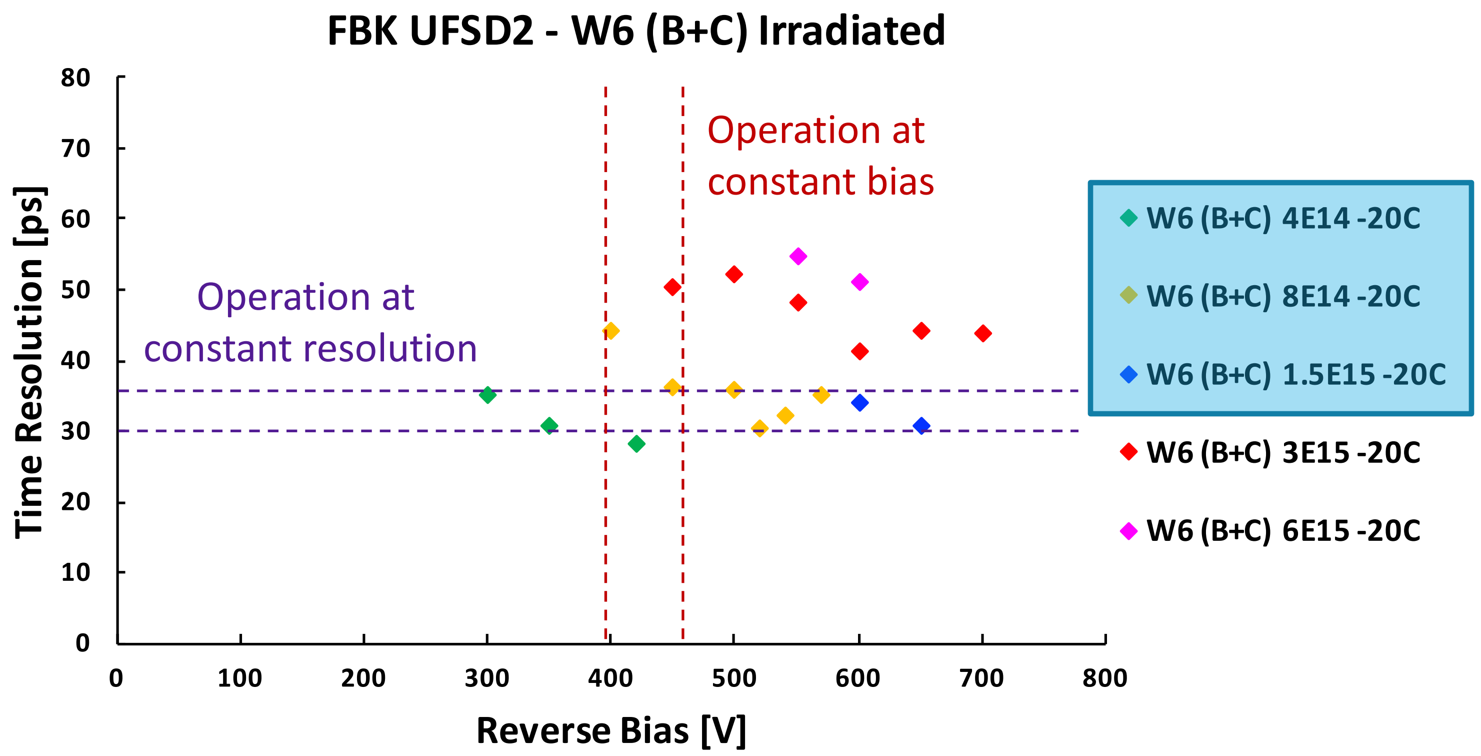




- ➢ SIMS measurements confirm this model: pre- and post-irradiated sensors have exactly the same Boron density in the gain layer region, however after irradiation, the Boron is not active any longer
  → **Controlled annealing to re-activate the gain layer under study**

Time Resolution with Carbon

CMS goal for silicon Endcap Timing Layer
Time resolution between 30-35 ps unchanged till the end of lifetime
(4000 fb^{-1} - 1E15 n_{eq}/cm^2)



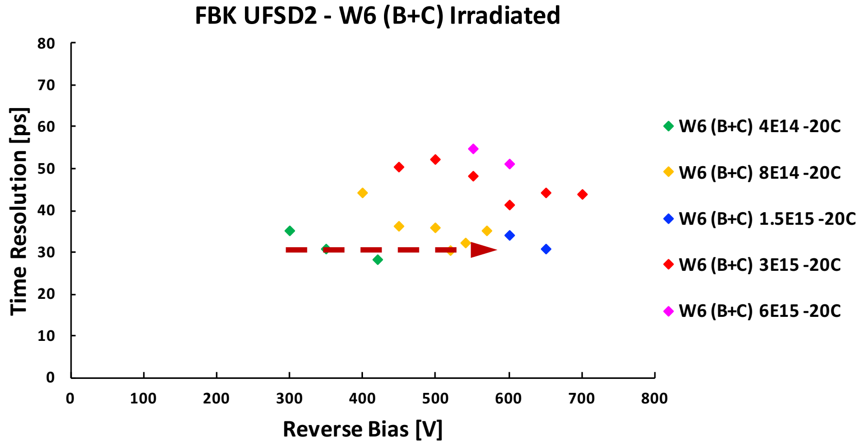
Possible to reach our goal with Carbonated LGAD

Plans for Sensor R&D Productions

Bias voltage difference from beginning- to end-of-lifetime detector to keep time resolution ~ 30-35 ps

300 V when NEW ⟶ 600 V @ 4000fb^{-1}

⇒ ΔV = 300 V along the full detector lifetime



Plans to further improve the radiation resistance in next FBK UFSD3 production

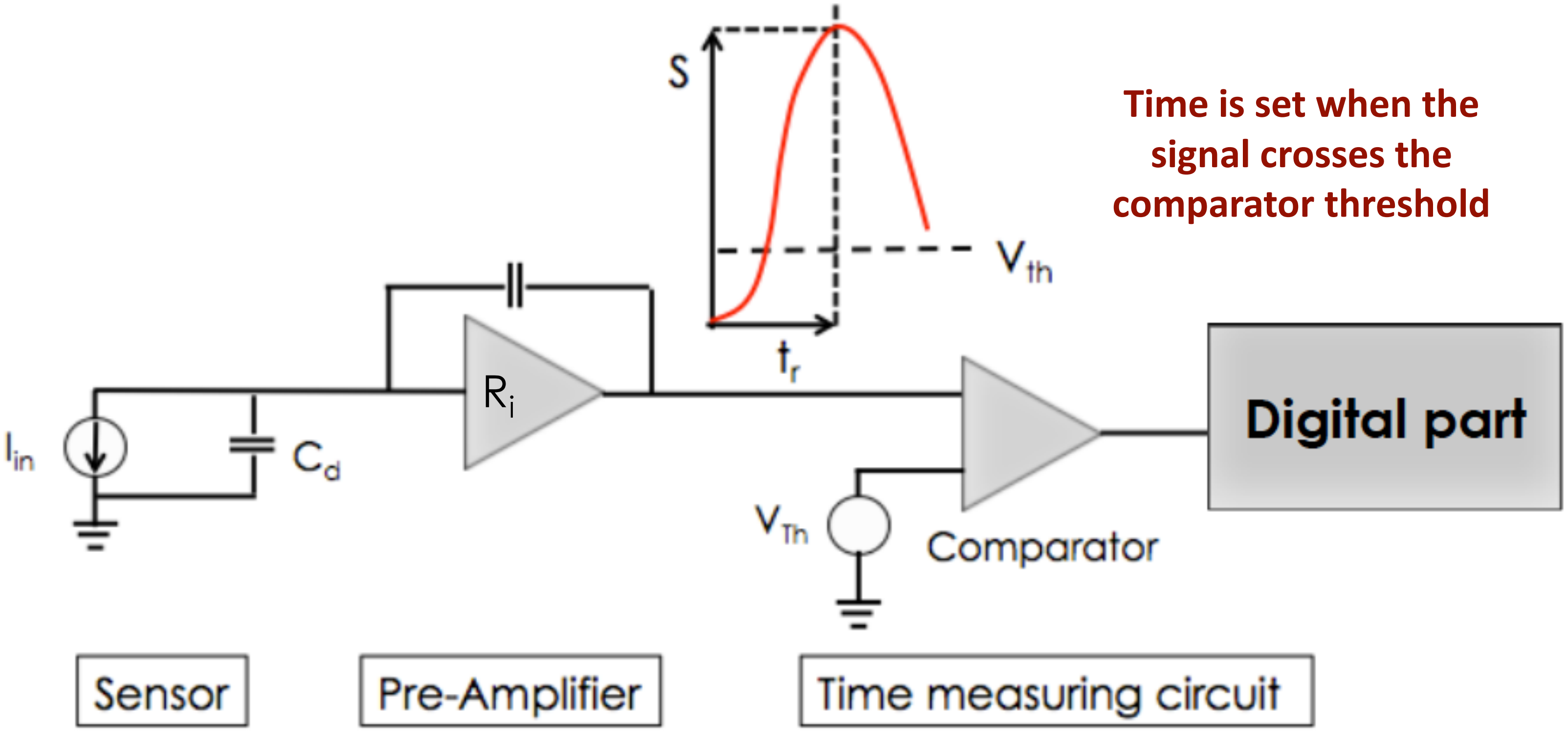
- Carbon dose optimisation
- Boron diffusion temperature optimisation
- Process sequence optimisation

The goal is to further reduce the ΔV along the full detector lifetime

☞ The dream would be to reach ΔV = 0V

CMS foresees 3 productions from 3 different vendors (CNM, FBK, HPK) to define the final ETL sensor design by the end of 2020

An Overview of the Front-End Electronics



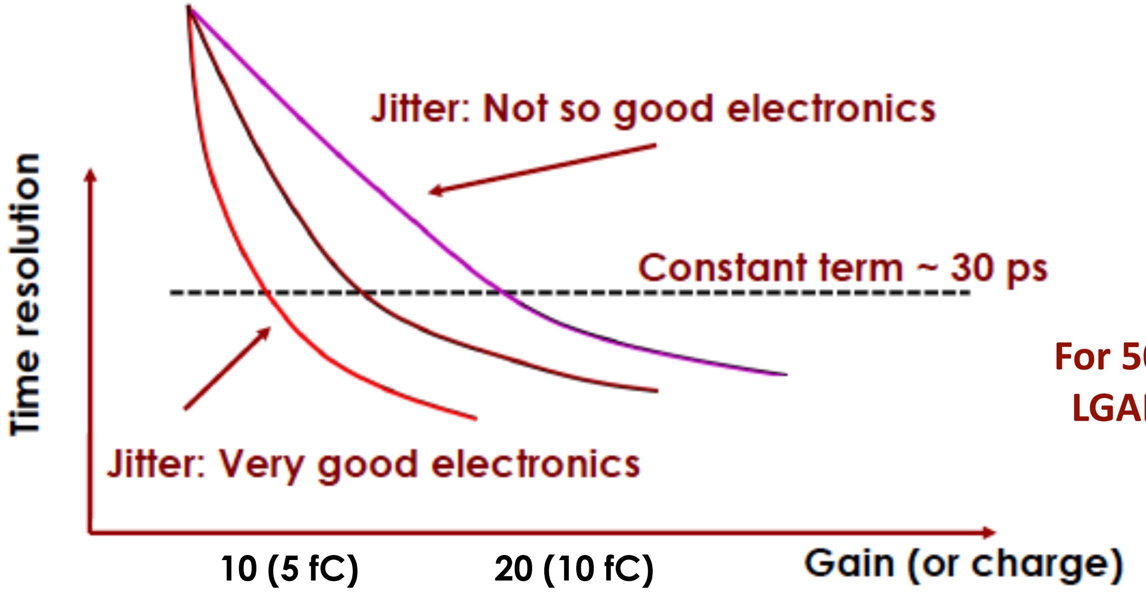
Time is set when the signal crosses the comparator threshold

- The analogue part plays a key role in the time resolution
- A front-end with very low input impedance that works in full current mode better exploits the fast signals from LGAD

$$\mathbf{R_i \times C_d < \text{Signal Rise Time} \sim 300\text{-}400\ ps}$$

Contributions to the Time Resolution

$$\sigma_t^2 = \left(\frac{N}{dV/dt}\right)^2 + \sigma^2_{non-uniform\ charge\ deposition}$$



For 50 μm thick LGAD sensors

Two components determine the time resolution:

- Non-uniform charge deposition → ~ constant term 25-30 ps
- Jitter contribution = N / (dV/dt) ~ 1 / Gain (**driven by the electronics**)

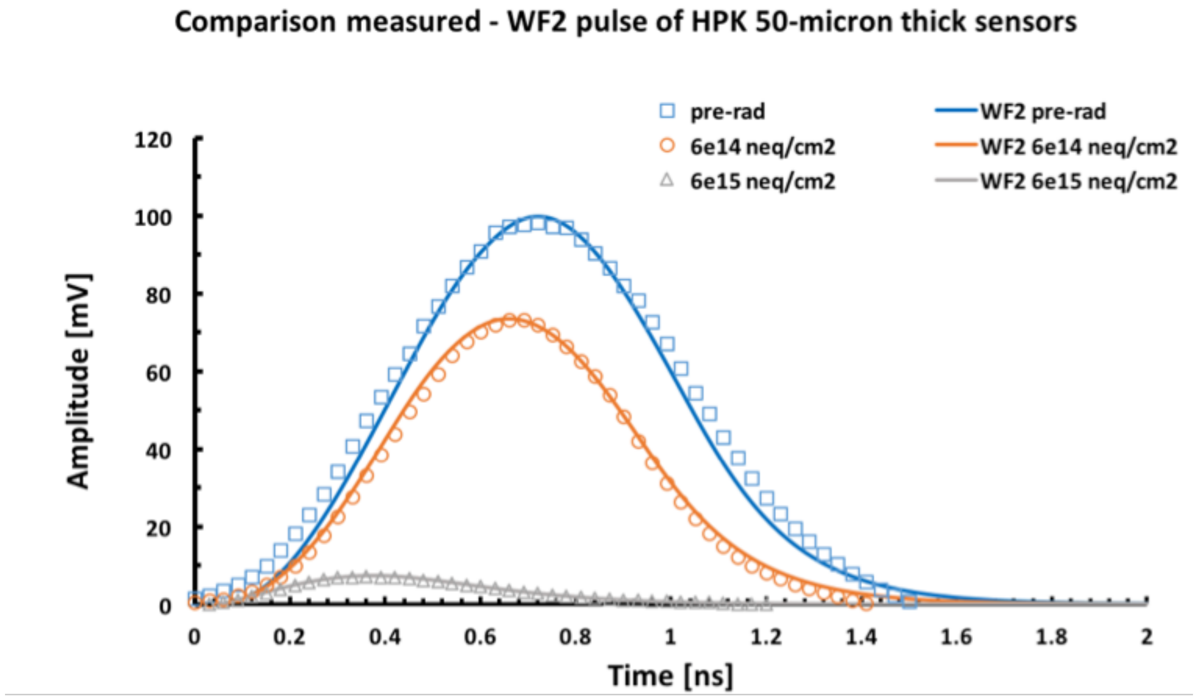
Goal for the front-end chip jitter ~ 20 ps

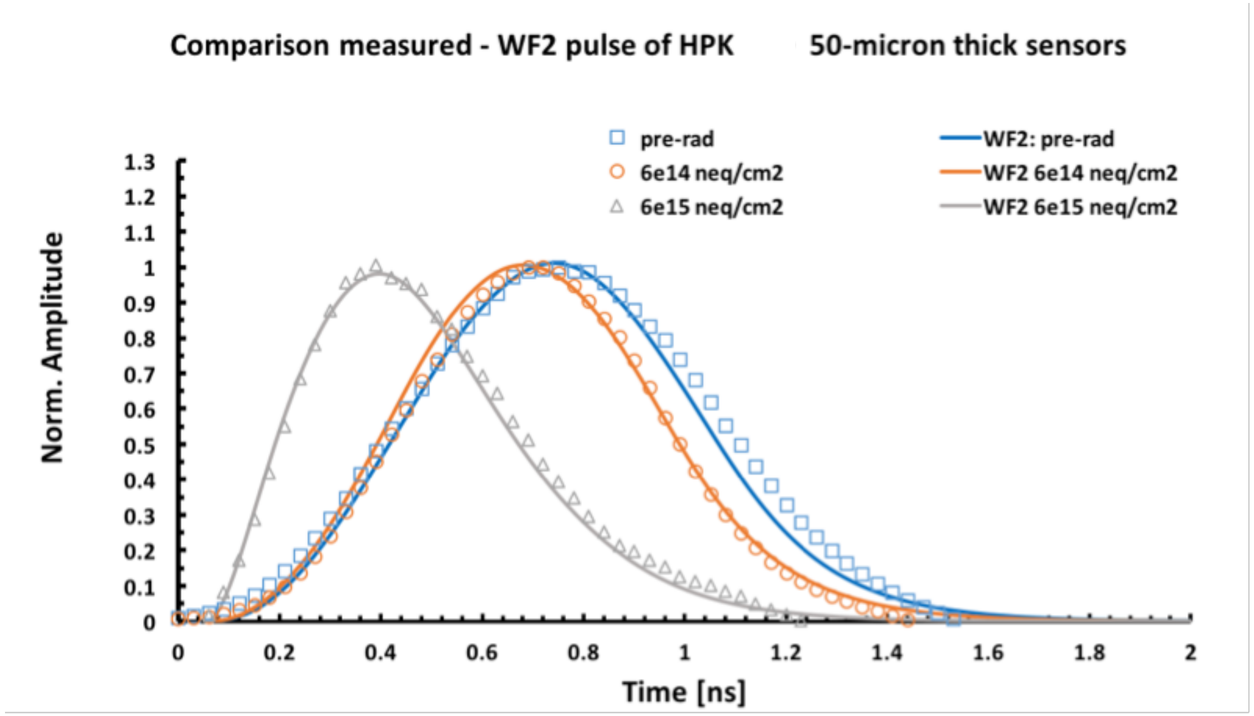
Evolution of the Signal with Fluence

With irradiation the LGAD signal becomes faster, shorter and smaller

Q : 10 fC → 2 fC

Rise time : 400 ps → 200 ps



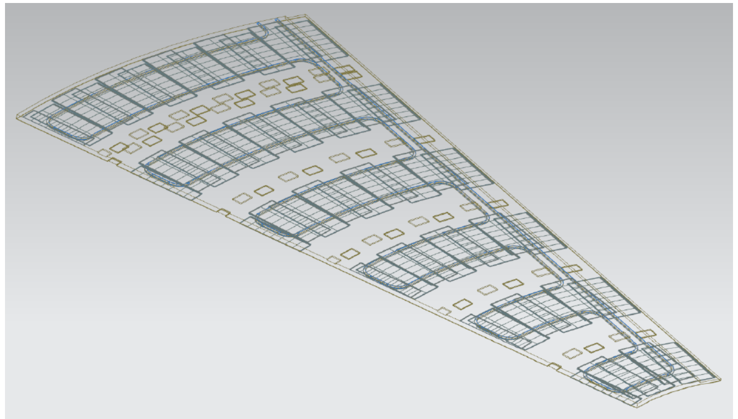


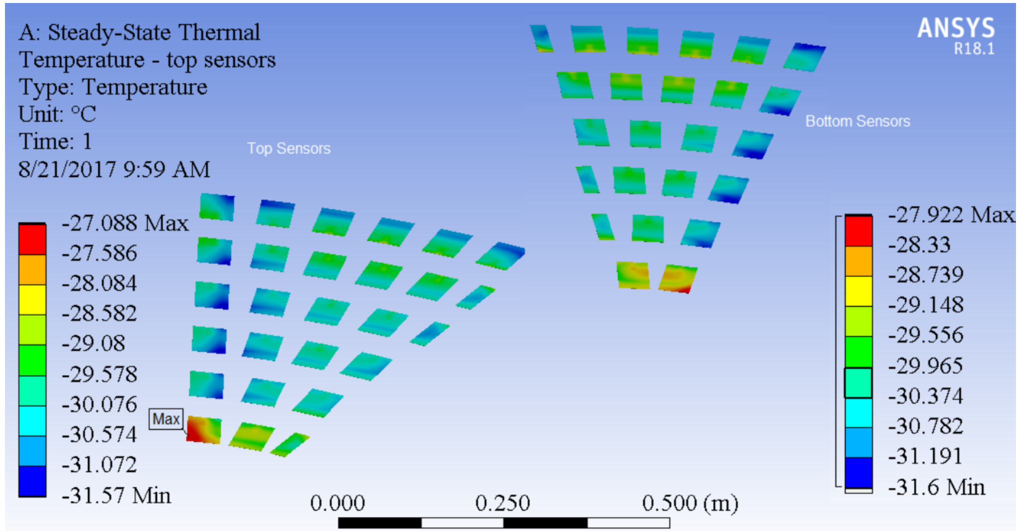
The signal tails change dramatically with irradiation, ToT might not work without constant calibration

☞ **Constant Fraction Discriminator is the safest option**

Mechanics and Cooling

- Endcap Timing Layer will be placed in an independent, thermally isolated volume on the nose of the Endcap Calorimeter detector, at a distance of about 3 m from the interaction point
- ETL modules will be mounted in rings on flat aluminium support structures, ensuring a continuous coverage in ϕ
- The power dissipated by the modules will be removed by a network of low-mass cooling pipes fed by a CO_2 cooling system separated from the other CMS detectors
- The heat generated on the modules will be transferred via the aluminium support to the CO_2 cooling pipes, keeping the silicon sensors at an operating temperature below -27° C
- **The cooling system allows for a power consumption of the read-out electronics of 100 mW/cm^2 for the read-out chip and ~ 3 mW per channel**





Clock Distribution

- ➢ A common R&D project for CMS Phase-II upgrades underway for a high precision clock distribution targeting 10 - 15 ps time resolution
- ➢ Two options kept open for timing detector:
  → LHC clock to each module encoded in lpGBT control links (no additional fibres needed)
  → Dedicated clock fibres + fan-out chip in case desired precision cannot be otherwise achieved
- ➢ Slow drifts or other low-frequency instabilities can be monitored and calibrated out with minimum bias data in-situ
- ➢ Also the ASIC design has to focus on ensuring that the clock can be distributed over a large area without introducing a jitter that would spoil the precision of the measurement

A CERN working group was formed between PH/ESE group and experiments to develop a High Precision Timing Distribution for High-Luminosity LHC (2024)
Progress track is available at https://indico.cern.ch/category/2388/

SUMMARY

- **First production of UFSD sensors with ETL geometry**
  - 4x24 pad sensors from CNM, FBK, HPK in production
- **Radiation tolerance**
  - Carbon inside the gain implant halves radiation effect
  - Possible to keep time resolution at 30-35 ps up to the total fluence expected for 4000 fb^{-1}
- **Front-End Electronics design crucial to maintain time resolution ~ 30 ps**
  - Avoiding signal integration fully exploits the fast signals from LGAD
  - Constant Fraction Discriminator is the best choice to read out signals from irradiated LGAD
- **Clock distribution is a key aspect for precise timing measurements**

⇒ 12 m^2 silicon detector for precise timing of MIPs is becoming real

ACKNOWLEDGEMENTS

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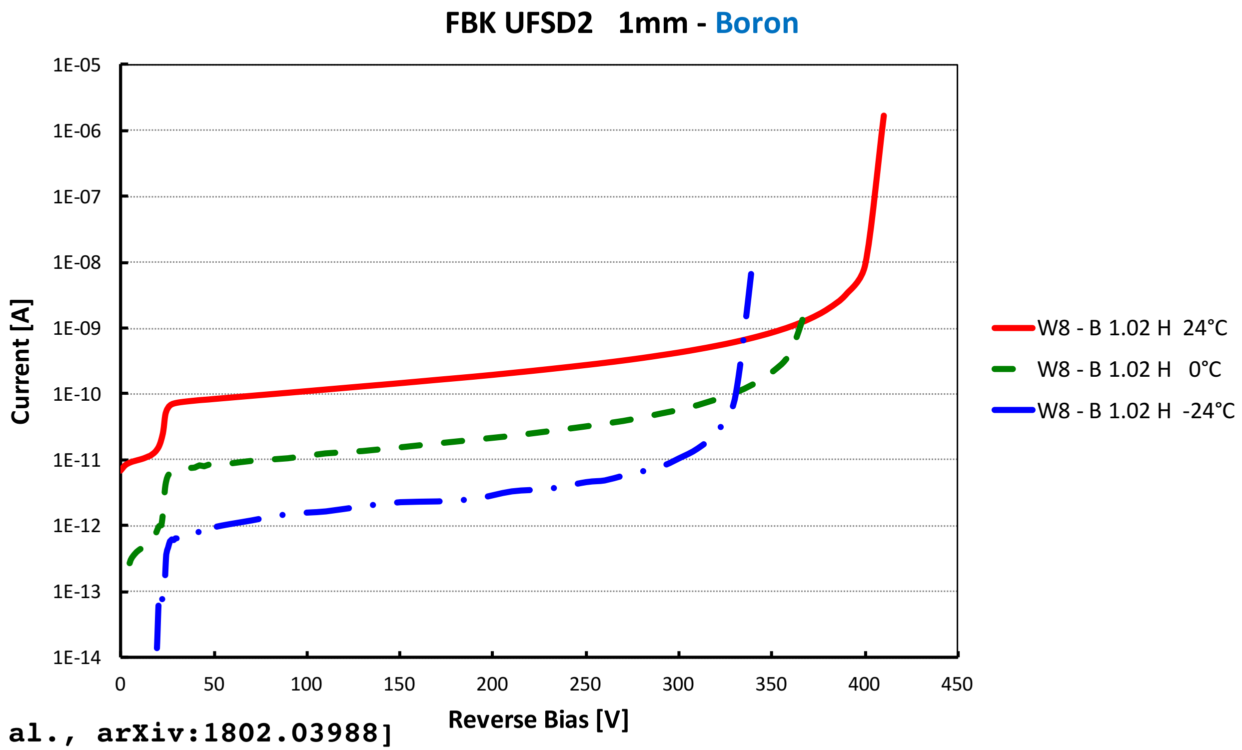
- Horizon 2020, grant INFRAIA
- AIDA-2020, grant agreement no. 654168
- U.S. Department of Energy, grant no. DE-SC0010107
- Fermilab LDRD, grant L2017.027
- RD50, CERN

IV Curves - Temperature Dependence

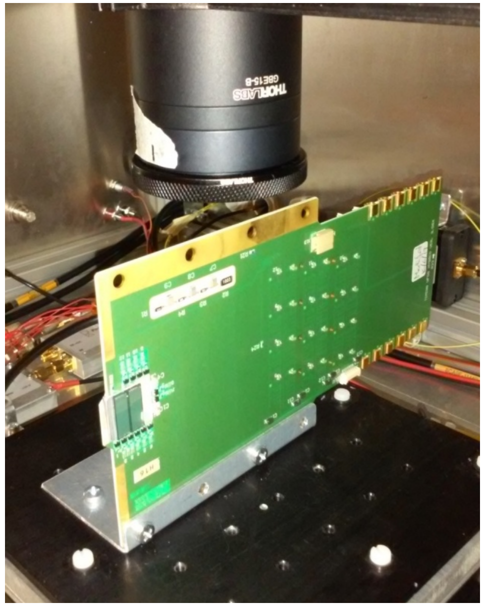


[V. Sola et al., arXiv:1802.03988]

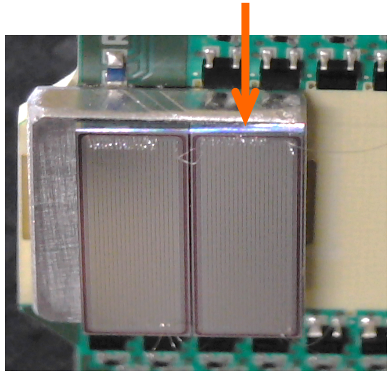
- Leakage current scales with the temperature (expected a factor 2 for every 7°C)
- Expected a gain inversely proportional to the temperature
- Internal Breakdown shift towards lower voltage due to the temperature decreasing

ΔT = 48°C → Current(24°C)/ Current(-24°C)~100 → Result expected

Intra-Strip Inactive Region



Laser beam



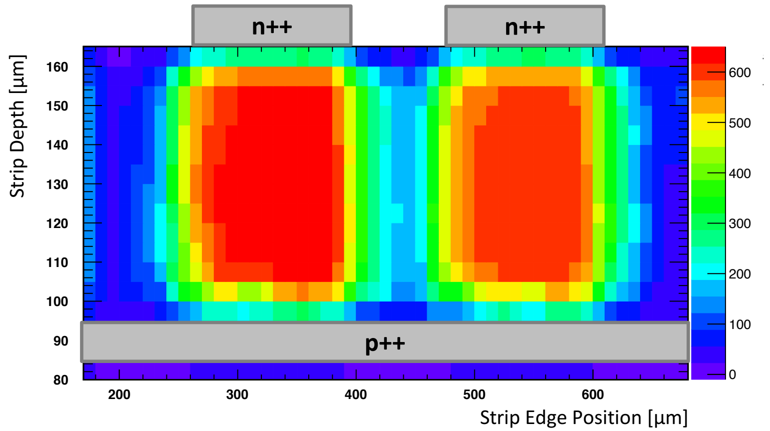
Edge TCT measurement to investigate the intra-structure inactive region

Pico-second IR laser at 1064 nm
Laser spot diameter ~ 10 µm
Multistage readout board by Pilsen University
Oscilloscope Lecroy 640Zi
Room temperature

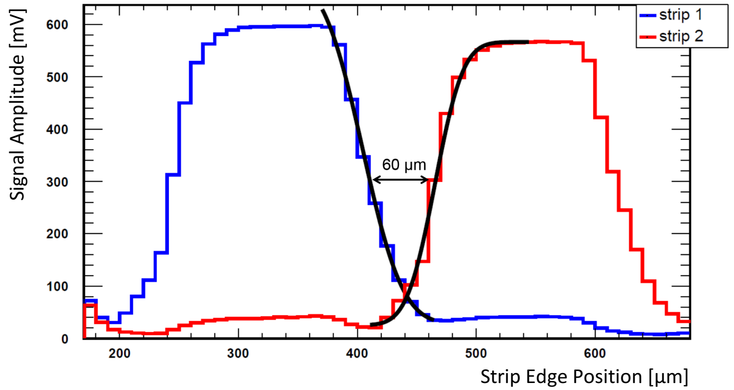
eTCT scan on 2 adiacent strip
W8 V_{bias} = 230 V

→ The inactive region between two adjacent strips has been measured to be ~ 60 µm

2D scan of two adjacent strip edge

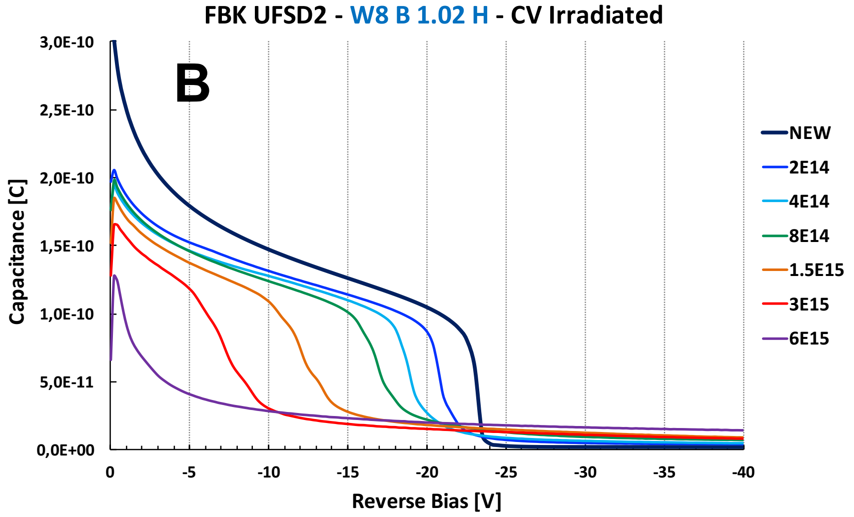


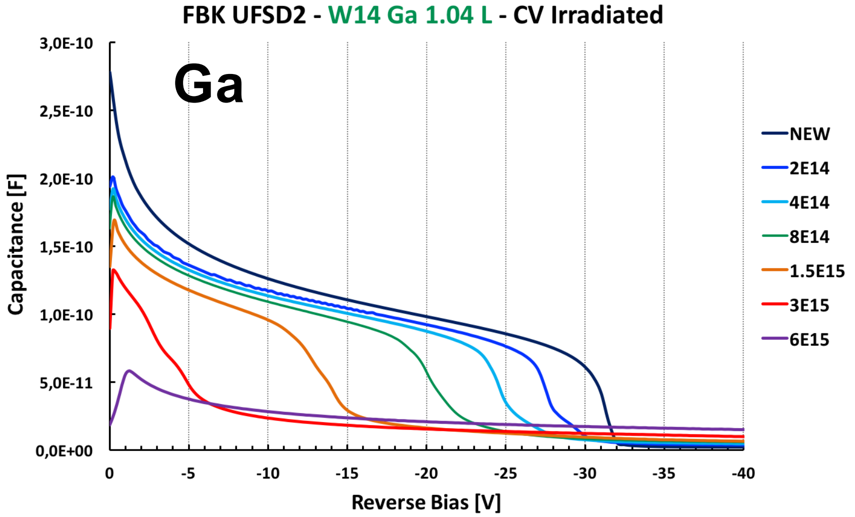
Signal amplitude projection - 2 strips



CV Measurements on Irradiated Sensors

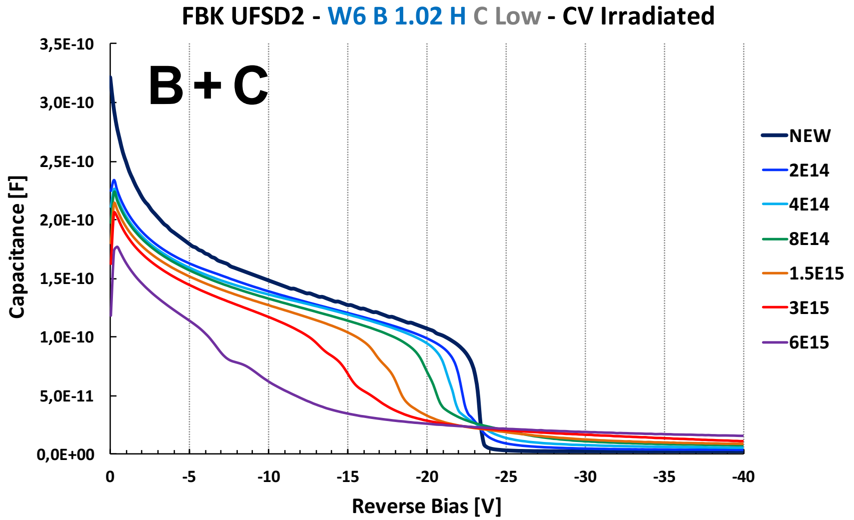
Standard

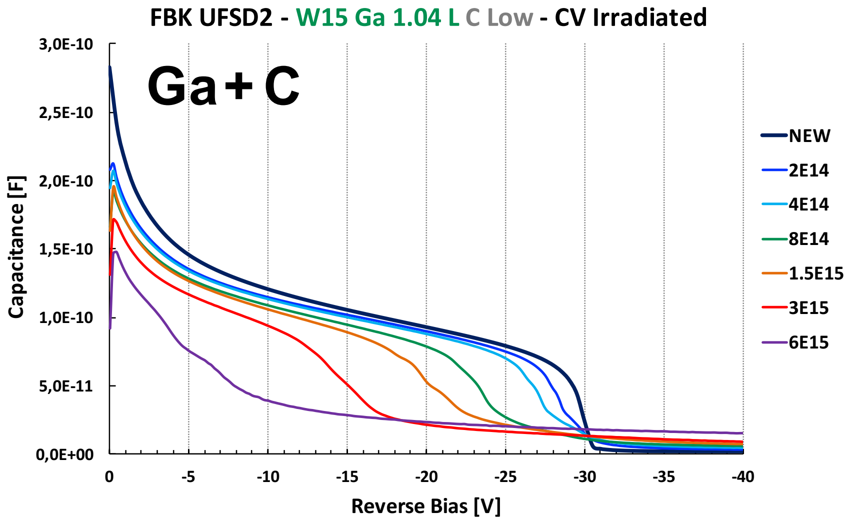




Reminder: fluence doubles at each step

Carbonated





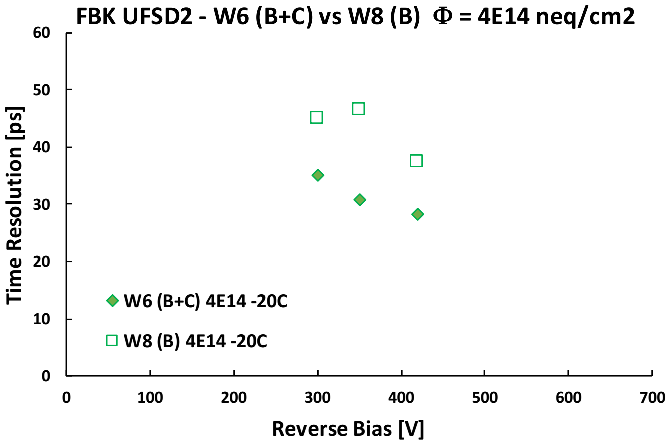
The knee voltage value is proportional to the gain layer doping

Time Resolution with and without Carbon

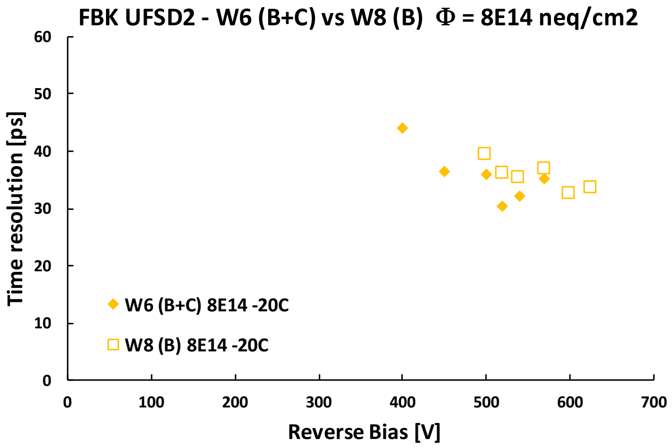
➢ **Sensors with Carbon maintain better time resolution at lower bias**

◆ **W6 - B+C**
☐ **W8 - B**

Φ = 4E14 n_{eq}/cm^2

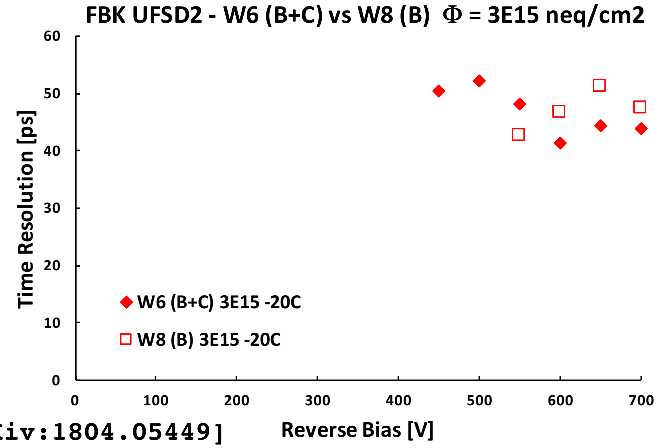


Φ = 8E14 n_{eq}/cm^2

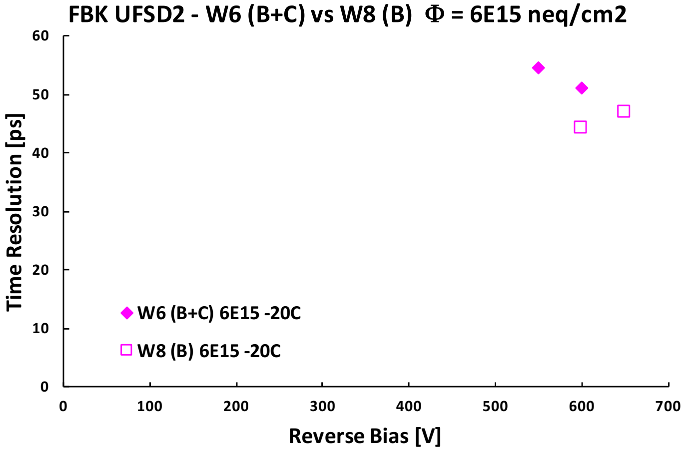


Time resolution measured with β source at -20°C

Φ = 3E15 n_{eq}/cm^2



Φ = 6E15 n_{eq}/cm^2



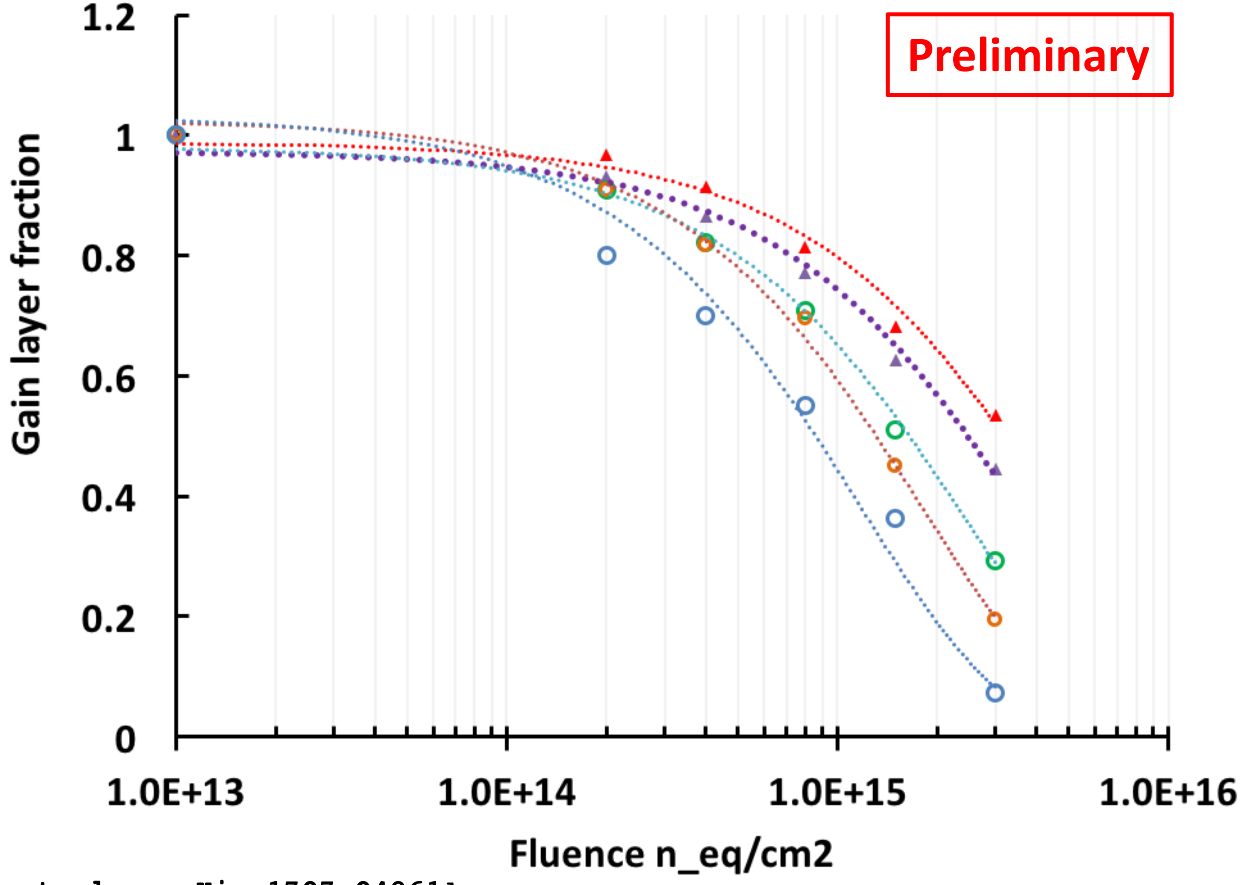
[S.M. Mazza et al., arXiv:1804.05449]

Acceptor Removal Coefficient

$$N_A = N_{A,0} - N_c \cdot (1 - \exp(-c \cdot \Phi_{eq}))$$

$$dN_A = -\sum_i c_i \cdot N_A \, d\Phi \quad , \quad c = \sum_i c_i([O],[C],[B])$$

From the fraction of gain layer surviving the radiation, it is possible to extract the acceptor removal coefficient c

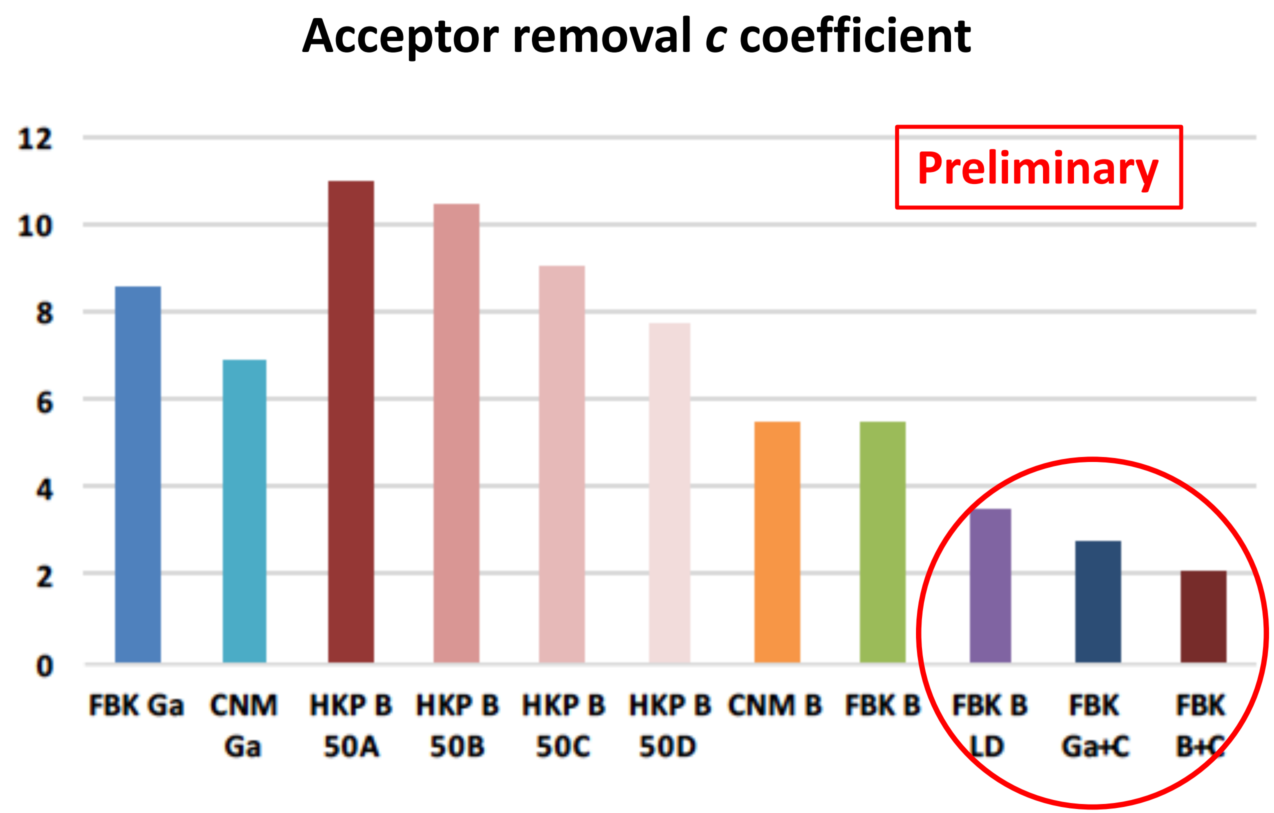


- $y = 9.9E\text{-}01e^{-2.1E\text{-}16x}$ W6 B+C - <CV>
- $y = 9.7E\text{-}01e^{-2.7E\text{-}16x}$ W15 Ga+C <CV>
- $y = 9.8E\text{-}01e^{-4.1E\text{-}16x}$ W1 LD <CV>
- $y = 1.0E\text{+}00e^{-5.5E\text{-}16x}$ W8 B <CV>
- $y = 1.0E\text{+}00e^{-8.5E\text{-}16x}$ W14 Ga <CV>

[M. Ferrero et al., arXiv:1707.04961]

Acceptor Removal Coefficient Distribution

HPK data courtesy of G. Kramberger



- Carbonated sensors have a factor ~ 3 better acceptor removal coefficient
- Among not carbonated sensors, low diffusion Boron has the better response to irradiation

→ **Will be Boron LD + Carbon the most rad-hard option?**