Characterization of irradiated RD53A pixel modules with passive CMOS sensors

Arash Jofrehei[1], Malte Backhaus[2], Pascal Raffael Baertschi[1], Florencia Canelli[1], Yannick Manuel Dieter[3], Jochen Christian Dingfelder[3], Franz Glessgen[2], Tomasz Hemperek[3], Fabian Huegging[3], Weijie Jin[1], Ben Kilminster[1], Anna Macchiolo[1], Daniel Münstermann[4], David-Leon Pohl[3], Arne Christoph Reimers[1], Branislav Ristic[2], Rainer Wallny[2], Tianyang Wang[3], Norbert Wermes[3]

1. University of Zurich (UZH)
2. ETH Zurich
3. University of Bonn
4. RheinMain University of Applied Sciences

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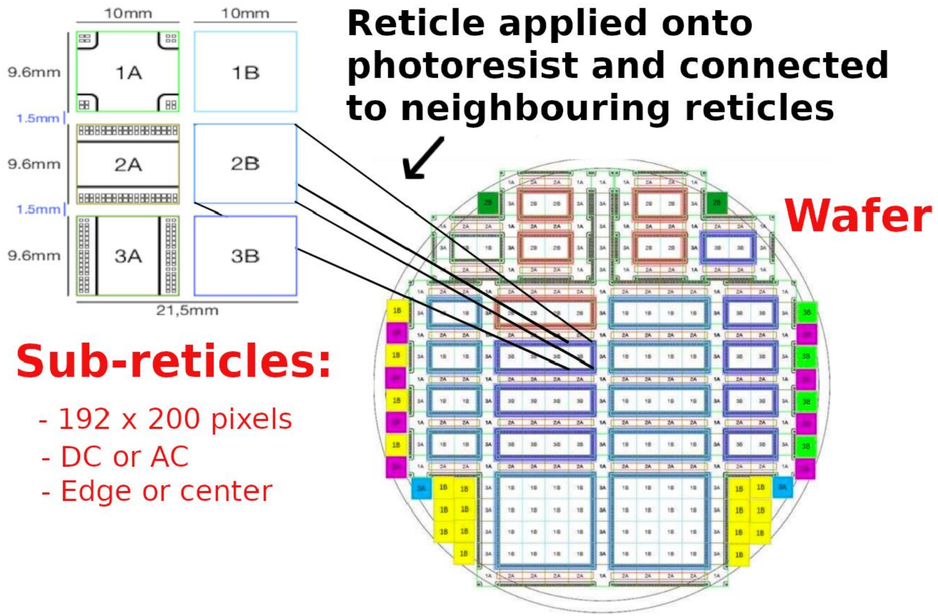
Introduction

- The LHC detectors to face challenging conditions in HL-LHC and beyond.
- The instantaneous luminosity of $5 - 7.5 \times 10^{34} cm^{-2} s^{-1}$ and pileup of 140-200 at HL-LHC.
- A fluence of $2 \times 10^{16}\ neq/cm^2$ expected for the CMS inner tracker first layer after 10 years of HL-LHC.
- A full replacement of the CMS tracker at Phase II upgrade before HL-LHC.
- CMOS technology is largely used in the semiconductor industry.
- The low production costs and the design precision and flexibility makes passive CMOS sensors an optimal candidate.
- Lab and beam tests performed to make sure they meet the criteria for running in the HL-LHC conditions.
- A joint effort between CMS and ATLAS colleagues.

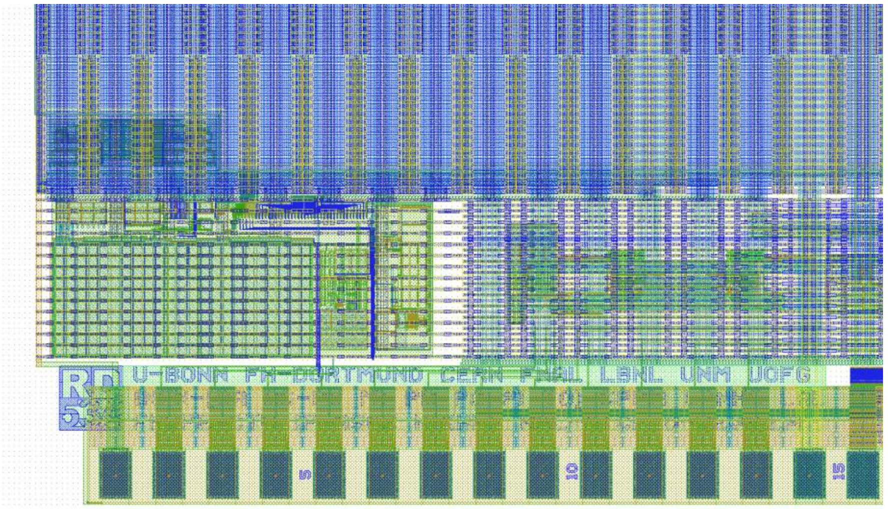
Sensors in LFoundry CMOS technology

- Building blocks in a reticule cell and stitching them.
- Produce layout on 8-inch wafers.
  - Reduction in the production cost wrt standard 6-inch sensor wafers used in HEP.
- CMOS technology → small on-pixel structures.
  - 4-6 metal layers for signal redistribution.
  - Possibility of mitigating leakage current noise with AC-coupled sensors.
  - Low and high-resistivity polysilicon layers.
- Pixel pitch of $25 \times 100\ (\mu m)^2$ and $50 \times 50\ (\mu m)^2$.
- First full wafer production of RD53A-compatible sensors.



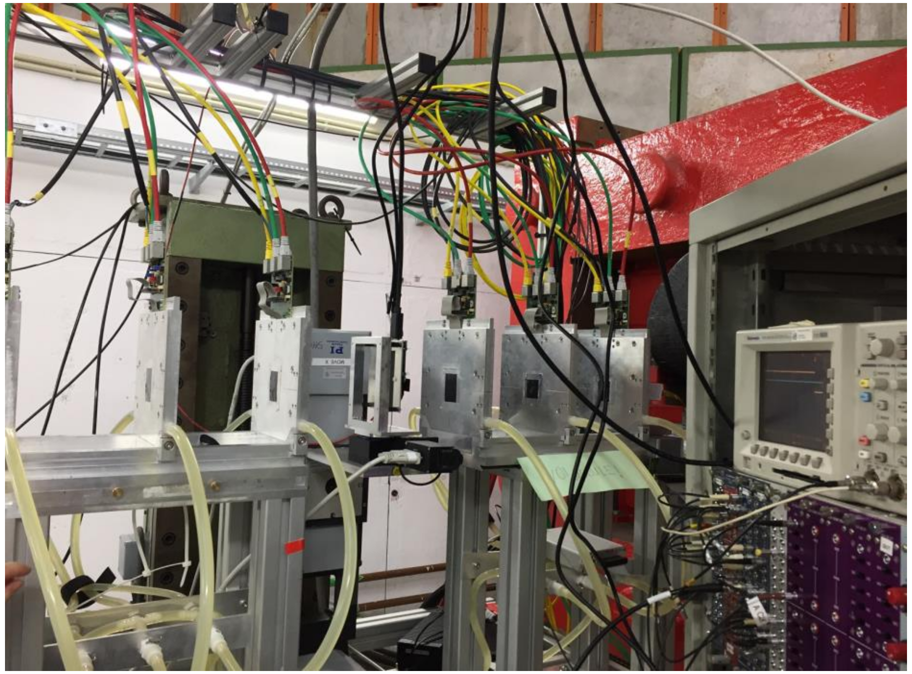
RD53A Readout Chip

- RD53A:
  - A prototype readout chip developed by the RD53 collaboration for ATLAS and CMS.
  - TSMC 65 nm CMOS production.
  - Consists of 3 Front-Ends (FE). CMS has chosen the linear FE and we only test this section.
  - $50 \times 50\ (\mu m)^2$ pixel pitch.
- Characterizing the sensors both in the lab and with a beam.
- Measurement and tuning of threshold, Time Over Threshold (TOT), …
- Readout by the [BDAQ53] and [Ph2_ACF] softwares.



Test beam @ DESY

- 5.2 GeV electron beam
- AIDA telescope with 3 upstream and 3 downstream planes.
- Detector Under Test (DUT) to be placed between planes 3 and 4.
- Precise DUT orientation and position control.
- Cooling box @ -35 °C
- Eudaq + BDAQ53 data acquisition



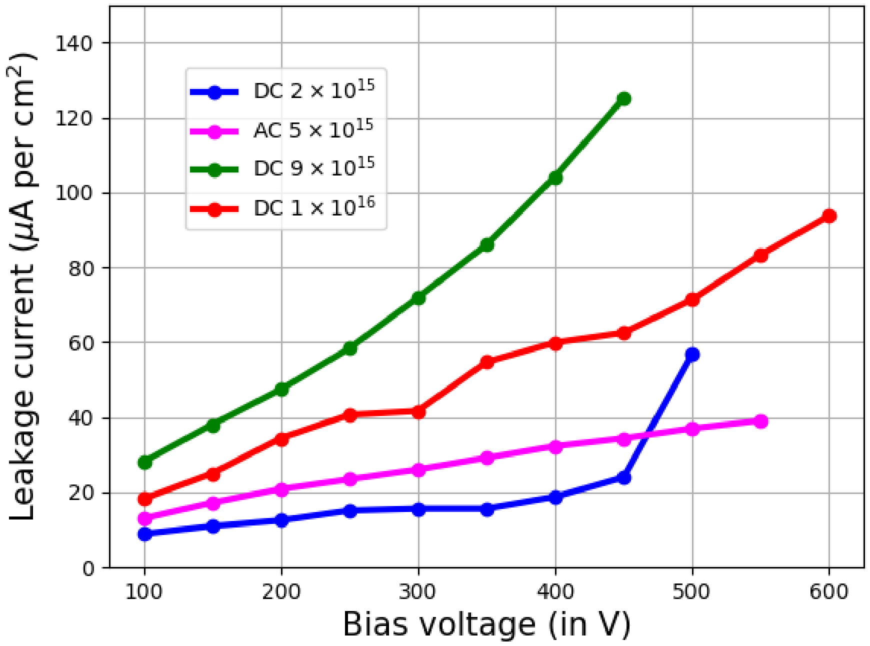
List of tested irradiated LFoundry sensors

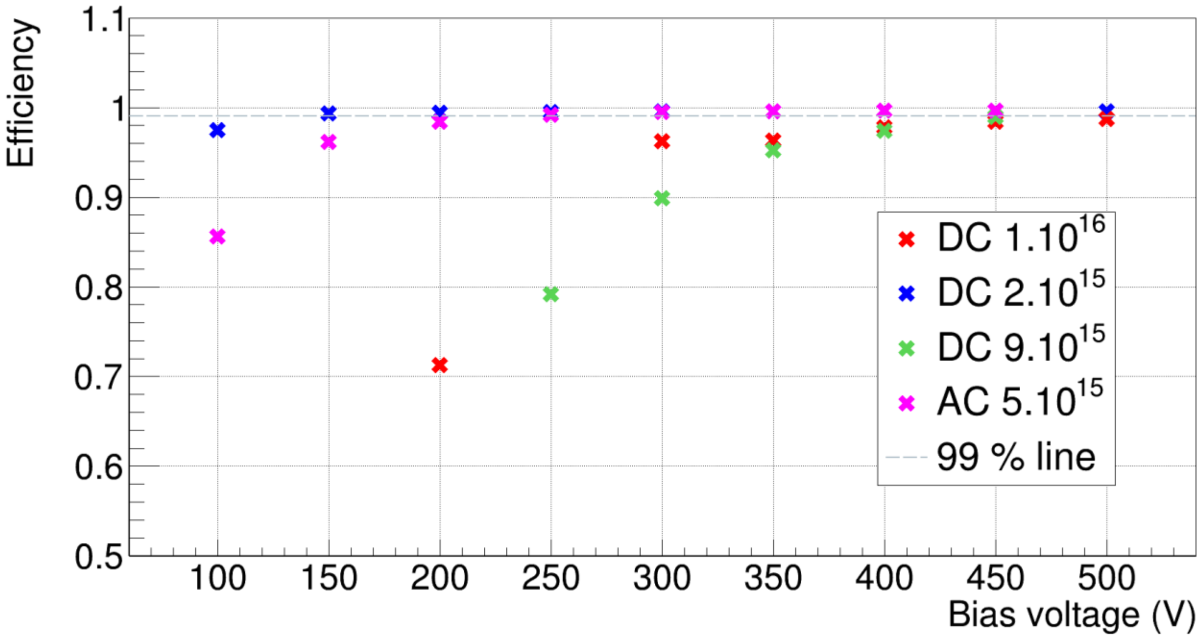
- 4 irradiated and 1 unirradiated single-chip LFoundry modules were studied at DESY in May 2021.
- Irradiation with 23 MeV protons at Karlsruhe.

Module	Pitch (μm^2)	Type	Fluence ($\frac{N_{eq}}{cm^2} \times 10^{15}$)	Threshold (e)
TBA1	25×100	DC	10	1192
TBA2	25×100	DC	2.1	1240
TBA3	25×100	DC	9.2	1219
TBA4	50×50	AC	5	1208

Efficiency and IV measurements

- Efficiency = $\frac{\#\ \text{matched hits}\ in\ \color{red}{DUT}}{\#\ expected\ hits\ from\ telescope}$
- DC $1 \times 10^{16}\ \frac{n_{eq}}{cm^2}$ reached 99% efficiency at 600V
- DC $2 \times 10^{15}\ \frac{n_{eq}}{cm^2}$ reached 99% efficiency at 150V
- The 4 irradiated modules were successfully biased to more than 450V as seen in the plots below.



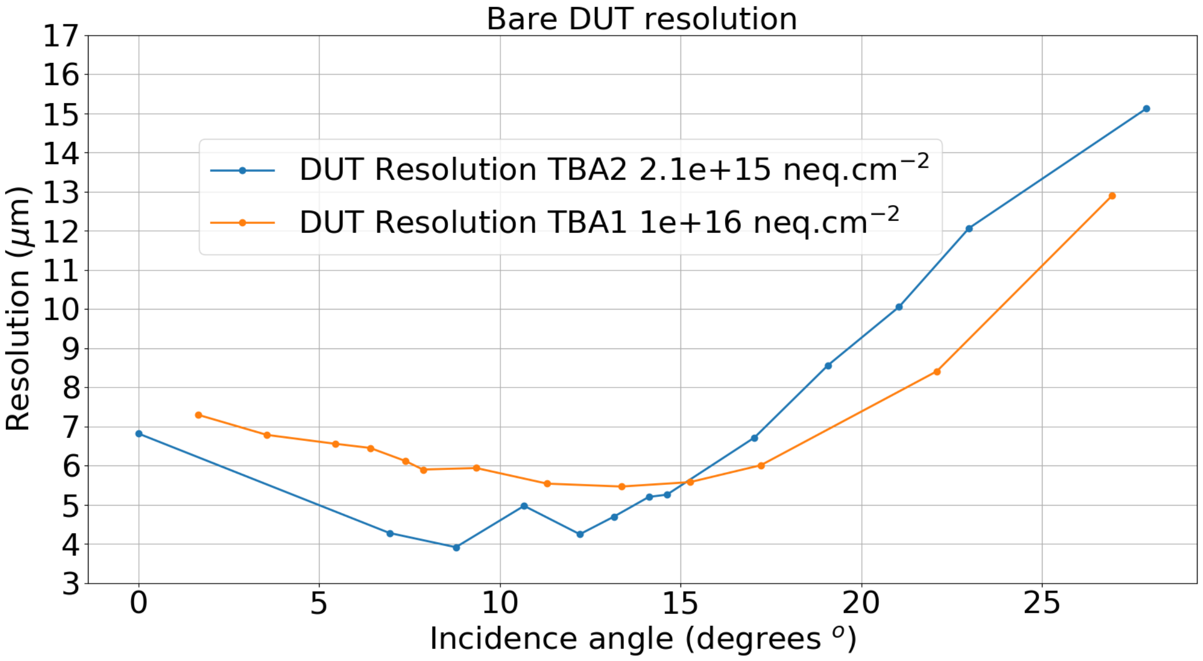


Position resolution

- Residual of hit position on DUT vs extrapolated track position
- Main contributions:
  - Telescope planes and extrapolation
  - Multiple scattering from the cooling box
  - Granularity of DUT
- Irradiated modules can be measured only in the cooling box $\rightarrow$ multiple scattering.
- Box contribution obtained by measuring an unirradiated module once inside and once outside the box.
- Telescope contribution calculated by comparing the extrapolated upstream and downstream tracks.

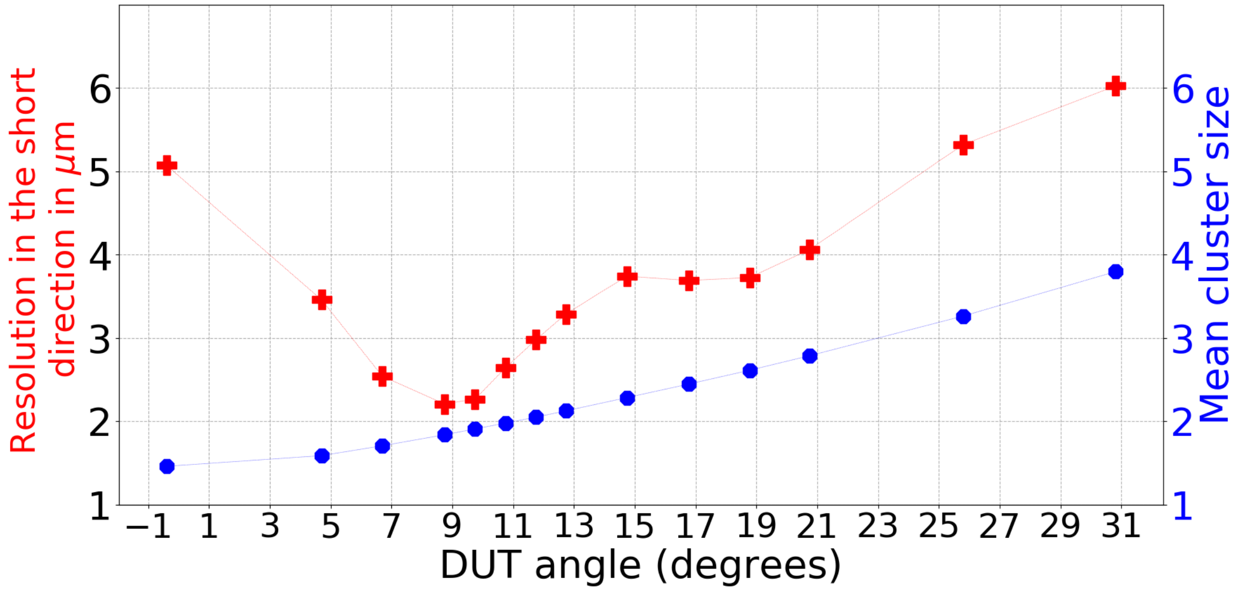
Position resolution at different incident angles

- The module is turned along the 25 μm side of the pixel cell.
- With a sensor thickness of 150 μm, the cluster width increases from 1 to 2 around the incident angle of 9.5 degrees.
- While cluster width of 1 gives a binary position and cluster width of 3 or more is prone to under-threshold charges, we expect the most precise position measurements to be at incident angles of 10-13 degrees.
- Achieved similar results wrt standard productions.



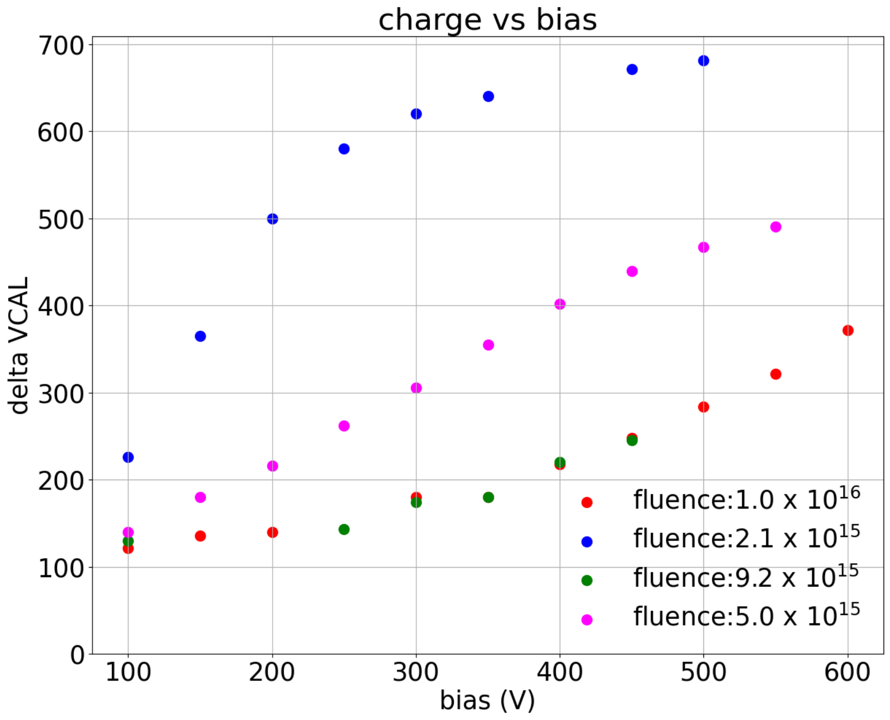
Previous results with unirradiated LFoundry

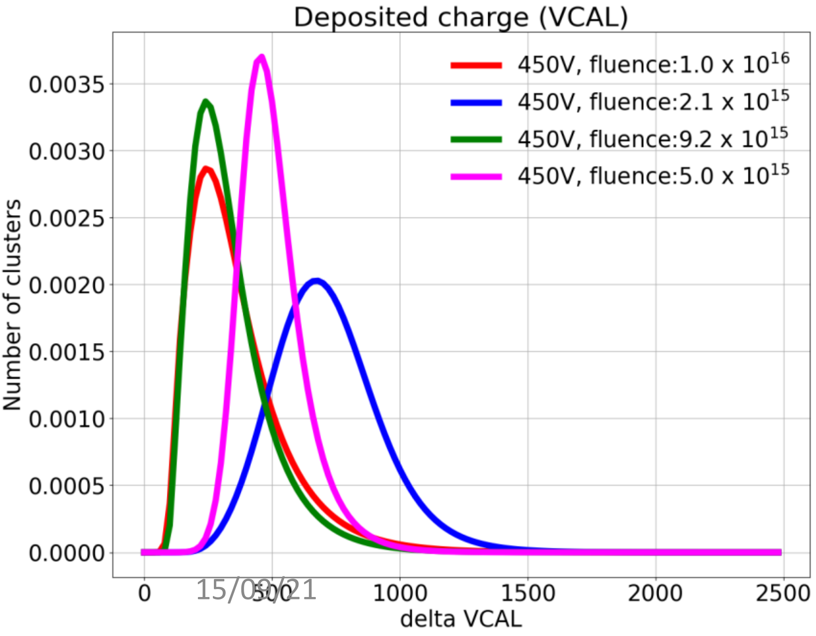
- Unirradiated LF RD53A modules were previously tested both in lab and with a beam.
- IV taken at 20°C and -20°C
  - All leakage currents within the Phase II requirements.
- Position resolution along the 25μm direction.

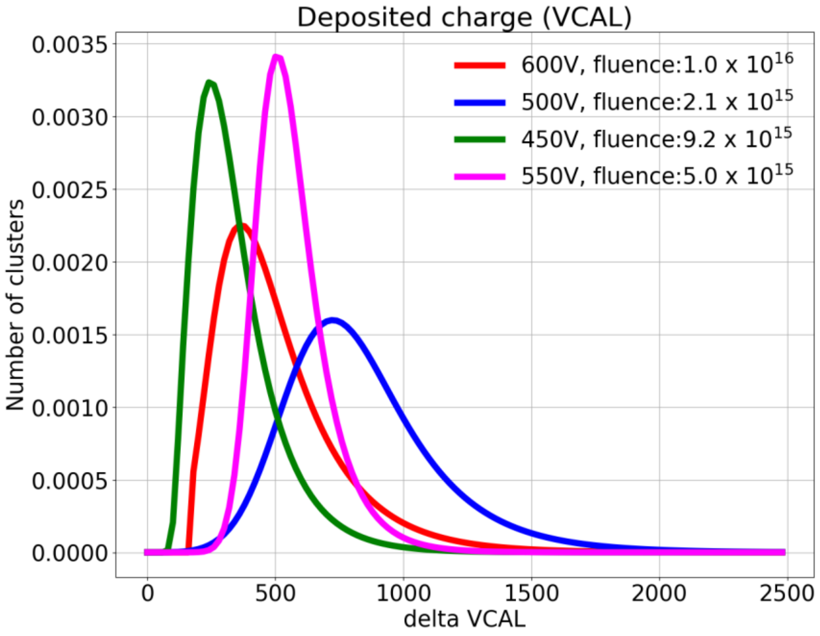


Charge Measurements at TB

- Calibrated charge in units of $\Delta(VCAL)$ vs HV.
- The distributions are plotted for:
  - All irradiated modules at 450V bias.
  - Each module at its highest achieved bias voltage.
- Relatively lower collected charge for higher fluences, as expected.

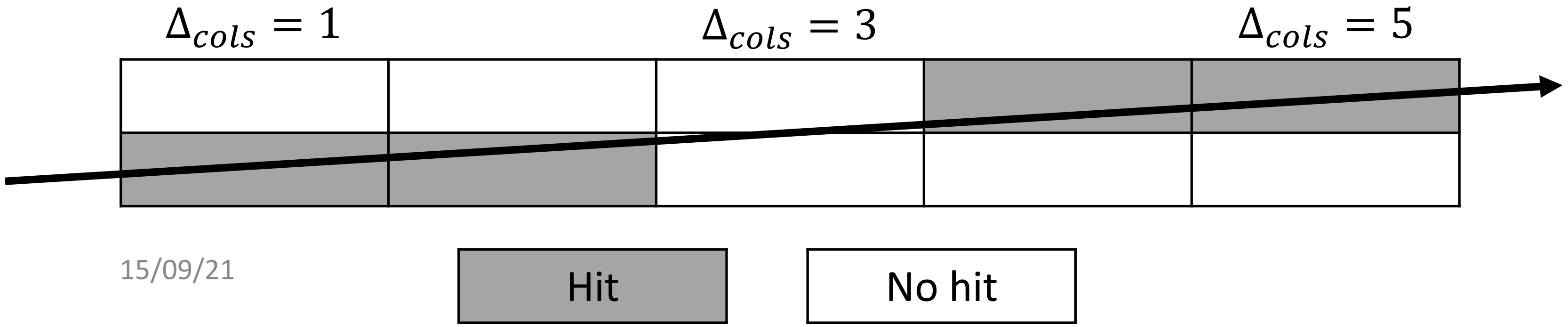


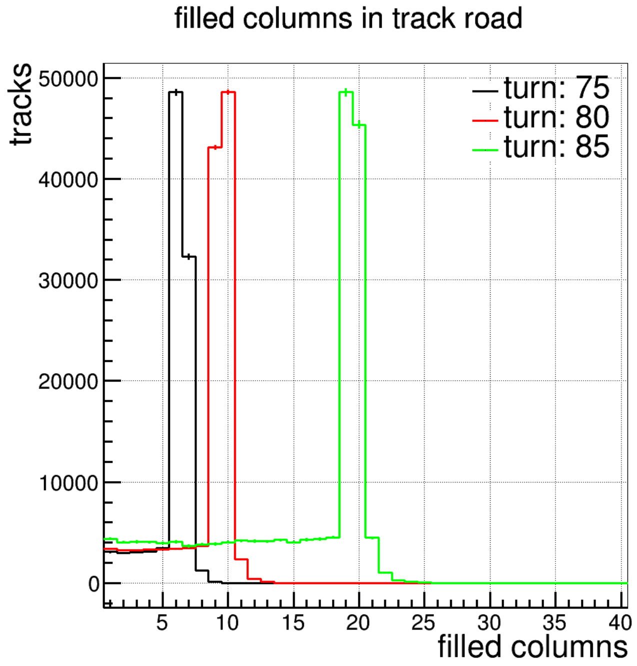


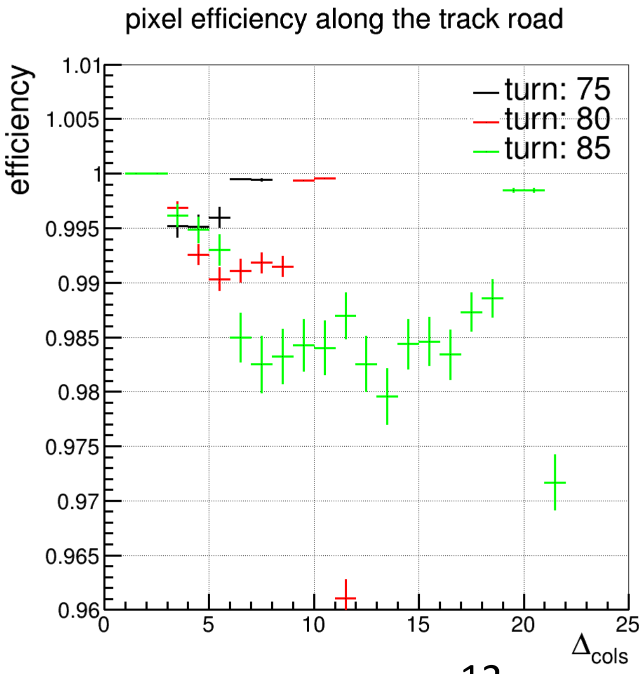


High η analysis

- The incident angle along η for the first layer of the CMS inner tracker can get up to 75-85 degrees.
- Challenges like cluster breaking arise in these high angles.
- Test beam analysis strategy:
  - Align the DUT and telescope tracks.
  - Define a "road" with a length of Δ_{cols} in which the track passes through DUT.
  - Look for pixel hits in the DUT around the track road.
- Top: Expected cluster length distribution based on the track.
- Bottom: For the most probable cluster length, pixel-to-pixel reconstruction efficiency.







Summary

- Irradiated RD53A modules with passive CMOS sensors were studied.
- Small on-pixel structures are possible using the CMOS technology.
- Stitching building blocks to produce large wafer reduces the production cost.
- Lab and test beam measurements show comparable performance compared to standard productions, meeting the Phase II requirements.