UNIVERSITY OF LIVERPOOL

VERTEX 2016

The 25th International Workshop on Vertex Detectors
25-30 September 2016

HIGH FLUENCE EFFECTS ON SILICON DETECTORS: DAMAGE AND DEFECTS CHARACTERIZATION

AN OVERVIEW OF THE STATE OF THE ART OF RADIATION RESISTANCE DETECTORS

Sven Wonsak, University of Liverpool
On behalf of the RD50 collaboration

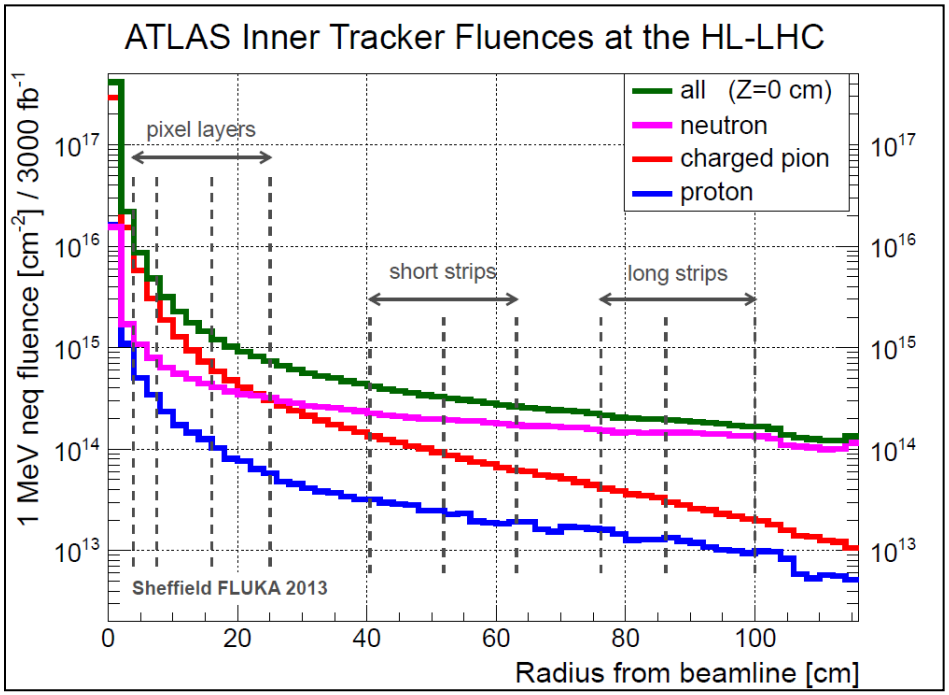
Outline

- Introduction & Motivation
- Measurement Methods
- RD50 detectors
  - 3D
  - LGAD
  - HV-CMOS
  - Slim/active edge
- Summary

This talk will only give a brief summary of some of the detector concepts investigated by the RD50 collaboration for radiation hard silicon devices.

Motivation

- LHC upgrade towards high luminosity (HL-LHC) after LS3 (~2024-26) expect 3000 fb-1
  - Semiconductor detectors will be exposed to fluences equivalent to more than 10^{16} n_{eq}/cm^2
- In future experiments even higher fluences can be expected, e.g. $7x10^{17}$ n_{eq}/cm^2 for FCC



[I. Dawson, P. S. Miyagawa, Sheffield University, Atlas Upgrade radiation background simulations]

- Further requirements are high granularity due to high occupancy and low material budget
- **RD50 has the mandate to develop and characterize radiation hard semiconductor sensors for very high luminosity colliders**

G. Casse and M. Moll; RD50 status report May 2016

The RD50 Collaboration

RD50: *52 institutes and 282 members*

42 European and Asian institutes

Belarus (Minsk), Belgium (Louvain), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), France (Paris, Orsay), Germany (Dortmund, Erfurt, Freiburg, Hamburg (2x), Karlsruhe, Munich(2x)), Italy (Bari, FBK, Perugia, Pisa, Torino), Lithuania (Vilnius), Netherlands (NIKHEF), Poland (Krakow, Warsaw(2x)), Romania (Bucharest (2x)), Russia (Moscow, St.Petersburg), Slovenia (Ljubljana), Spain (Barcelona(2x), Santander, Valencia), Switzerland (CERN, PSI), United Kingdom (Birmingham, Glasgow, Lancaster, Liverpool, Oxford)

6 North-American institutes

Canada (Montreal), USA (BNL, Brown, Fermilab, New Mexico, Santa Cruz, Syracuse)

1 Middle East institute

Israel (Tel Aviv)

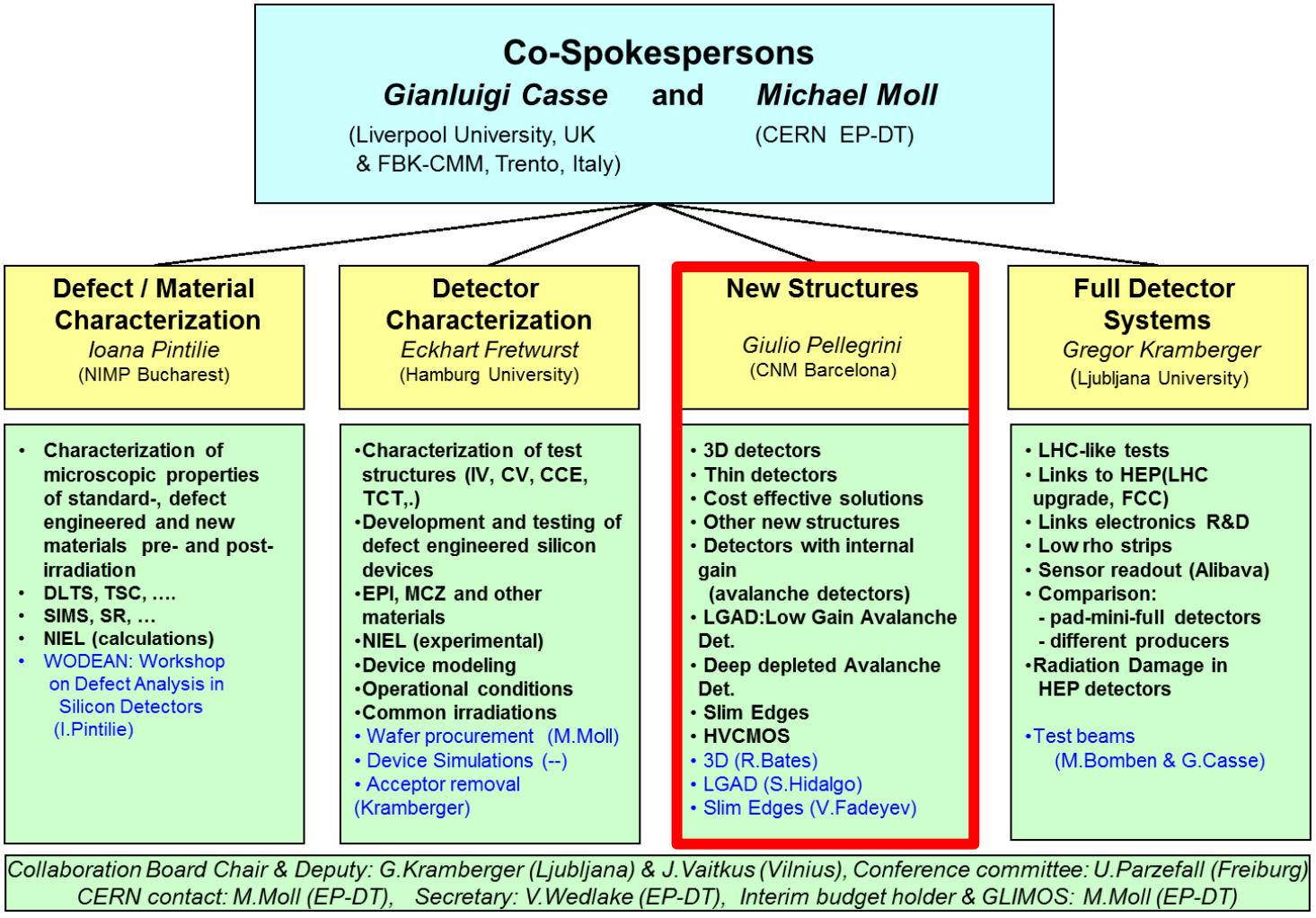
1 Asian institute

India (Delhi)

Detailed member list: http://cern.ch/rd50

M. Moll; September 2016

RD50 Organizational Structure



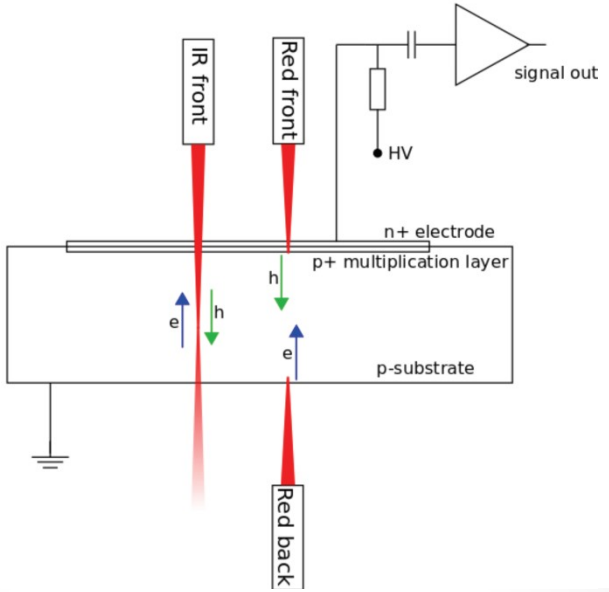
This talk: New Structures

Further talks at this workshop
Ioana Pintilie: Experimental techniques for defect characterization of highly irradiated materials and structures

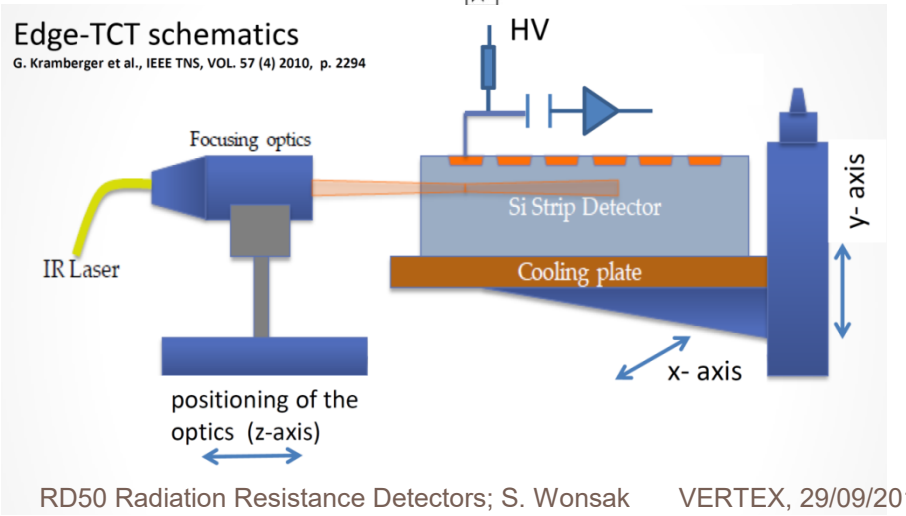
Gregor Kramberger: Radiation damage models, comparison and performance of TCAD simulation

TCT / eTCT

- Transient Current Technique:
  - Induce electron/hole pairs with a laser
    - Red light → surface
    - Infrared light → bulk
  - TCT: laser access to top or bottom of device
    - Surface scan
  - eTCT: laser access to the edge of the device
    - Allows the reconstruction of
      - The electric field
      - The charge collection profile

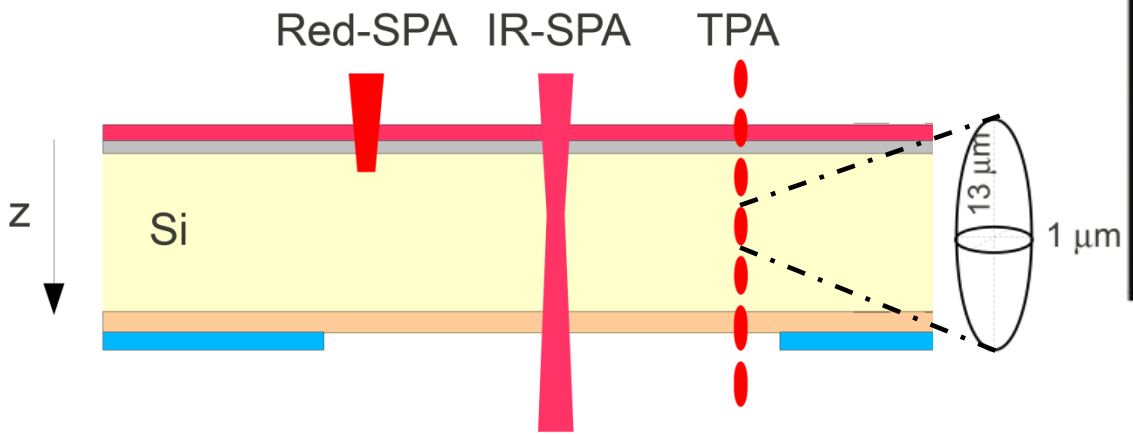


S. Otero Ugobono; 28th RD50 workshop

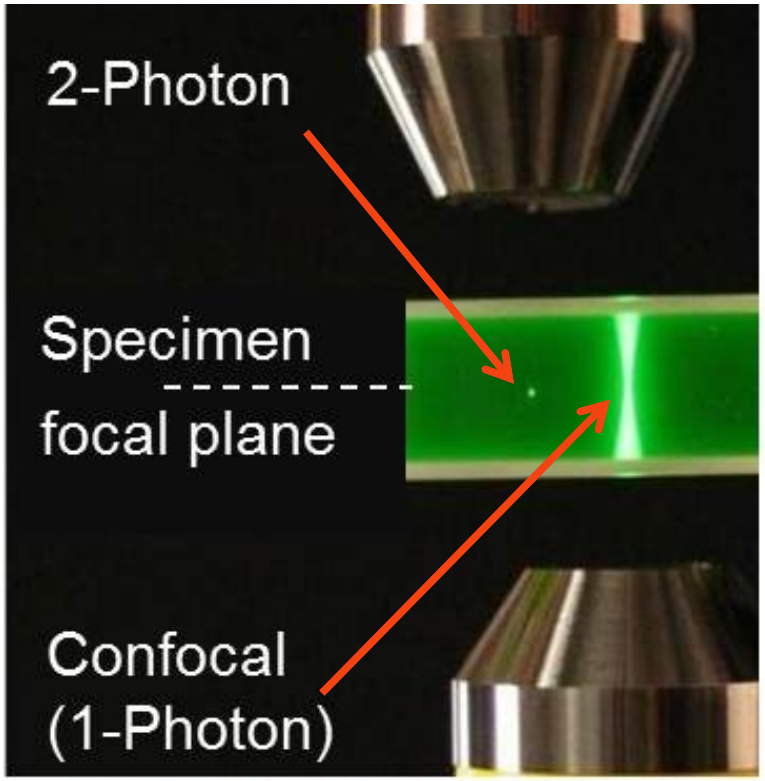


Two Photon Absorption

- New measurement method, based on TCT idea
  - TPA-TCT is a way to generate very localized electron-hole pairs in semiconductor devices
    - High resolution 3D mapping of devices possible
  - Conventional top-TCT configuration (laser enters from diode-junction side)
  - More accurate study of pixelated sensors
  - Less relevance of metal-induced beam reflections



M. Frenandez; 28th RD50 workshop

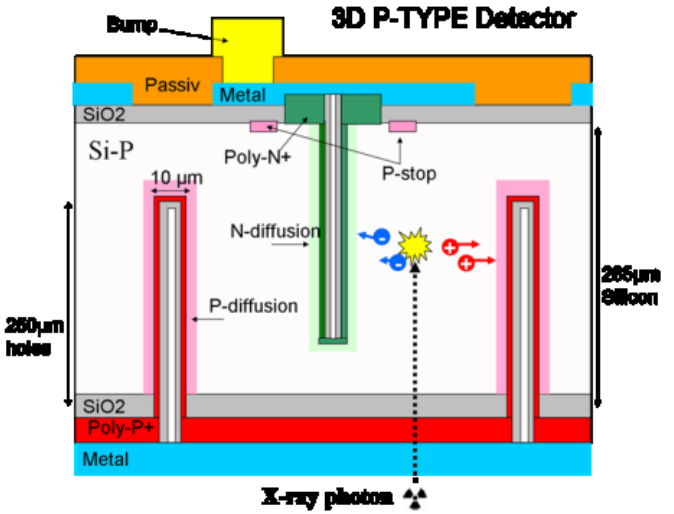


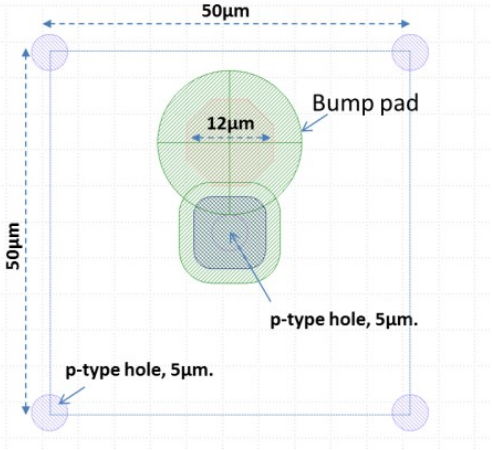
Photography: Ciceron Yanez, University of Central Florida

I. Vila; 26th RD50 workshop

3D

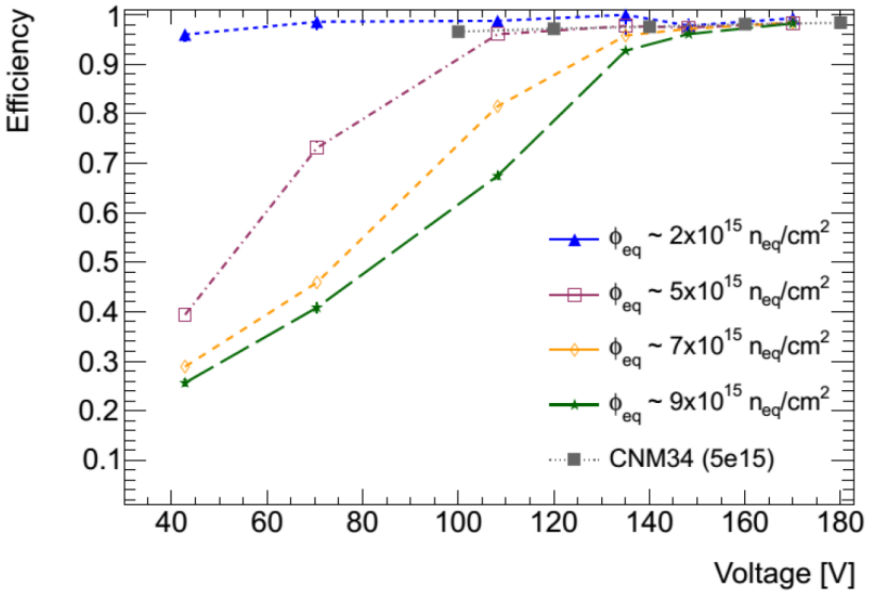
- Doped columns in bulk material
  - Electrode distance decoupled from sensitive detector thickness
    - Lower full depletion voltage and smaller drift distance
  - p^+ and n^+ columns, one used for biasing and the other for readout => depletion region between the columns rather than from the segmented side to the backside
  - Columns etched from the surface into the bulk
    - Single sided: both etched from the top
    - Double sided: columns of one type etched from the top, the others are etched from the bottom
  - Allows slim edge
- Can be either used as pixel sensors with each readout column as pixel, or combining several readout columns to a strip by a common implant on the sensor surface





3D

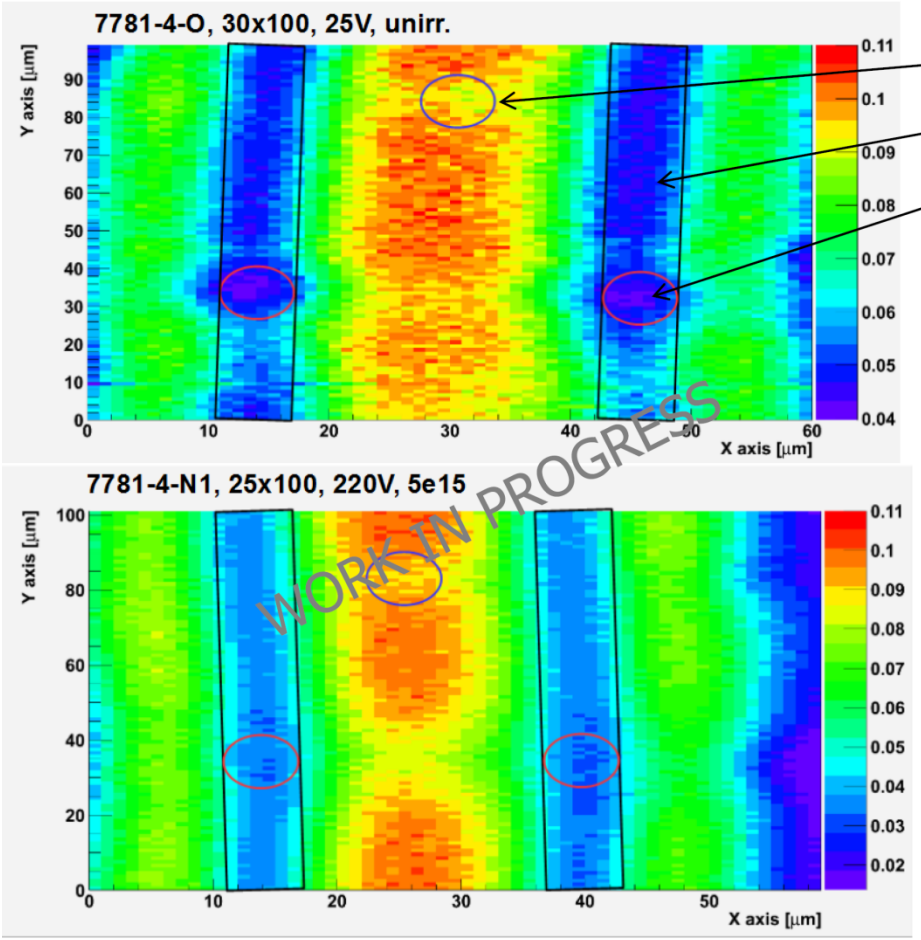
- Challenges
  - Complex production process (lower yields, higher costs)
  - Higher capacitance => higher noise
  - Non uniform response from 3D columns and low field regions
- Applications:
  - ATLAS IBL: 25% 3D detectors, running since June 2015
    - Detectors produced by CNM and FBK
  - ATLAS Forward Proton (AFP): running since march 2016



J. Lange; 28th RD50 workshop

Non-uniformly p-irradiated IBL 3D pixel sensor(FE-I4) at CERN (PS IRRAD)
9.4x10^{15} n$_{eq}$/cm^2
97.8% efficient at 170V

3D strip sensors



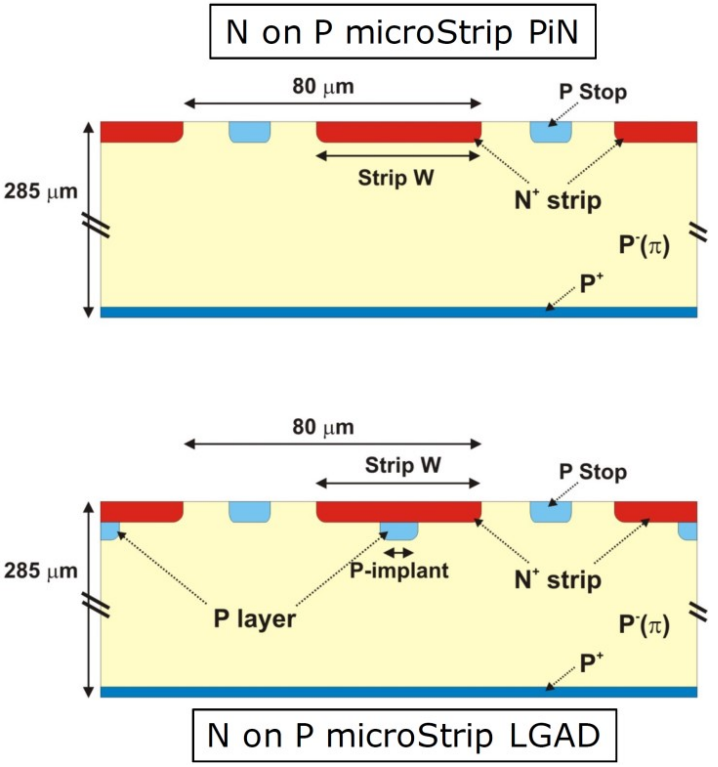
- Surface scan with 1060 nm IR laser
- 2 readout strips (here summed charge)
  - Normalised to beam monitor
- Still working on TCT optimisation and charge uncertainty determination, measurements and analyses still ongoing
- Successful, relative uniform charge collection even after $5x10^{15}$ n_{eq}/cm^2

J. Lange; 28th RD50 workshop

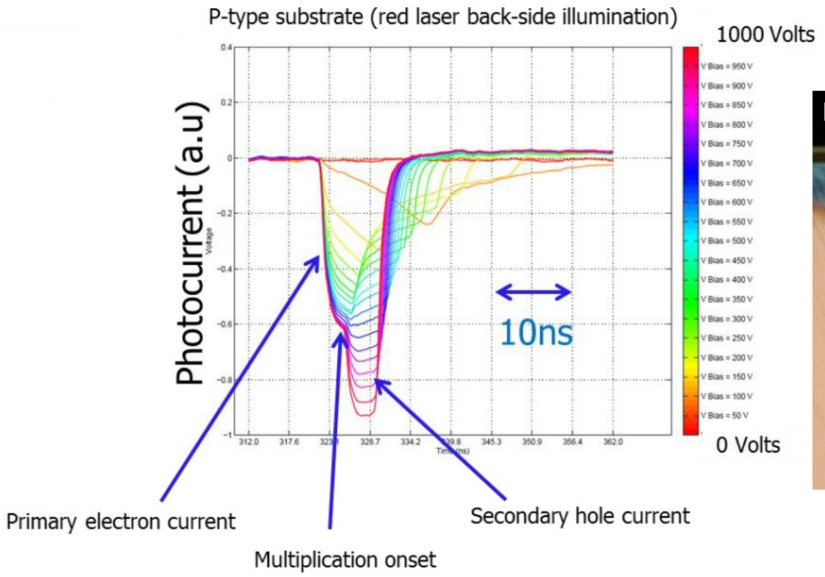
LGAD

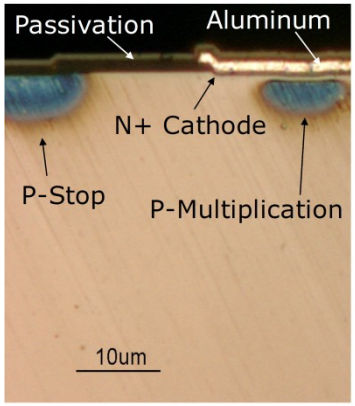
Low **G**ain **A**valanche **D**etector

- Integrated signal amplification while maintaining similar noise levels and avoiding read-out front end saturation
  - Utilizing avalanche multiplication, caused by high electric field
  - Highly doped implant under strip to create high electric field



- Characteristic signal in TCT measurements





S. Hidalgo; 27th RD50 workshop

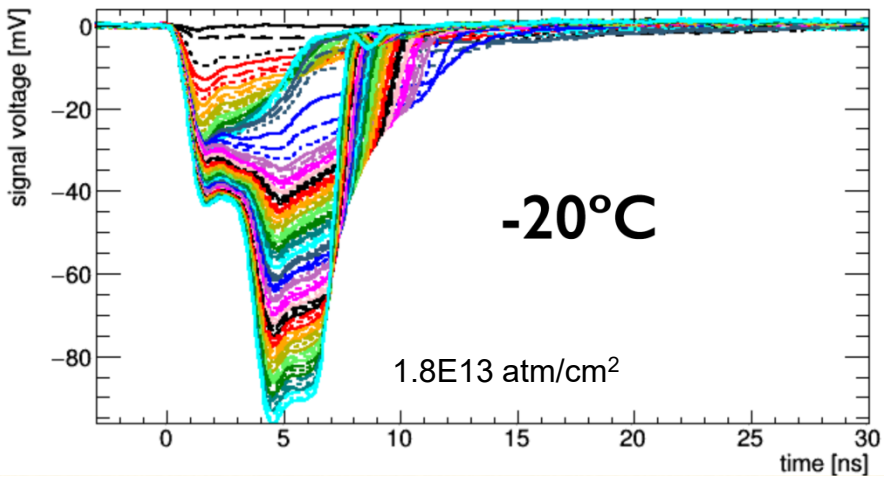
I. Vila; 28th RD50 workshop

LGAD

Different production runs at CNM

- Multiplication layer doping material
- Multiplication layer doping dose
- Substrate thickness

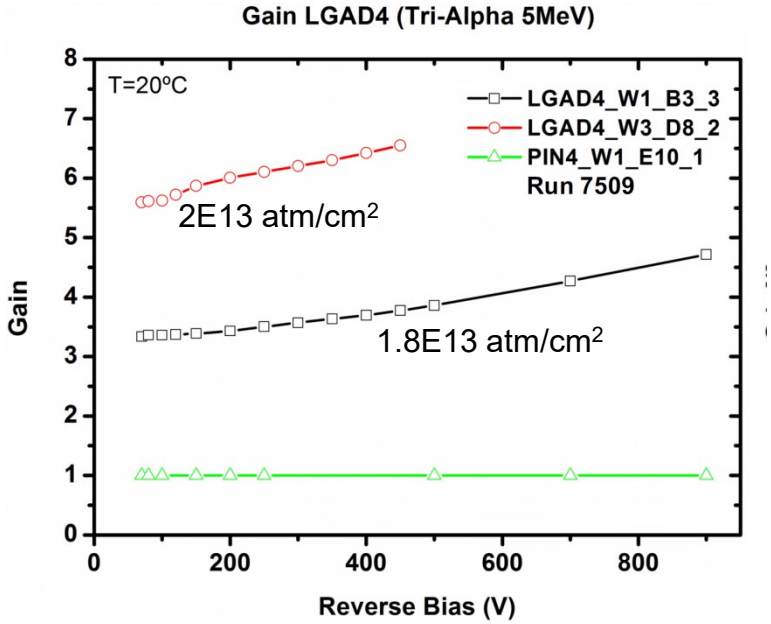
TCT red; back side; Run 7859
LGAD_4_W2_I3-1; 10^{14} n_{eq}/cm^2



S. Otero Ugobono; 28th RD50 workshop

Both runs: Boron with 300µm substrate

Run 7509; Charge collection with alpha source from backside

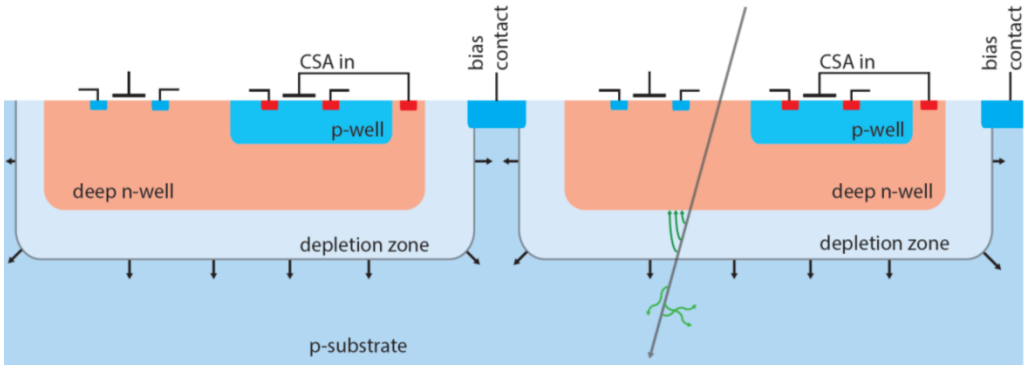


S. Hidalgo; 27th RD50 workshop

HV-CMOS

- New way of using commercial CMOS technology for particle physics detectors
  - Experimenting with different technologies (AMS, X-FAB, LFoundry)
- High-voltage CMOS technology
  - In-pixel amplification
  - Also in-pixel processing electronics possible
  - Very small pixel sizes possible
  - Thin wafers possible without performance loss
- Possible to use capacitive coupling through glue instead of bump-bonds
- Fully monolithic devices don't require a bump-bonded read-out chip

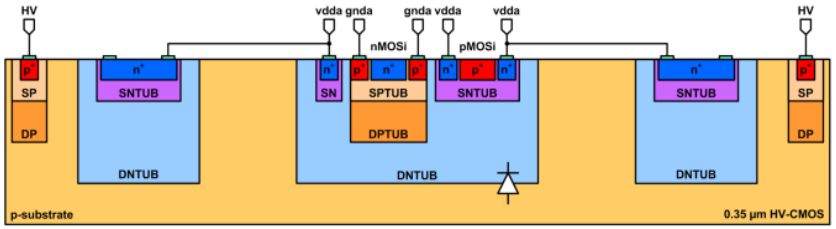
- Low resistivity p-substrate (10-20 Ωcm) and deep n-well form pn-junction
- Deep n-well also the bulk material for additional MOS structures
- Charge is mainly collected via drift by deep n-well



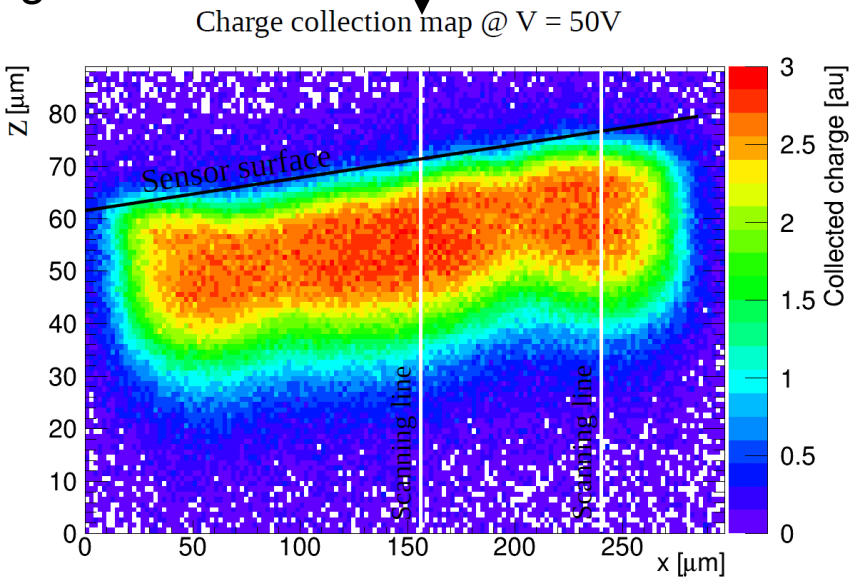
S. Fernandez Perez; TWEPP 2015

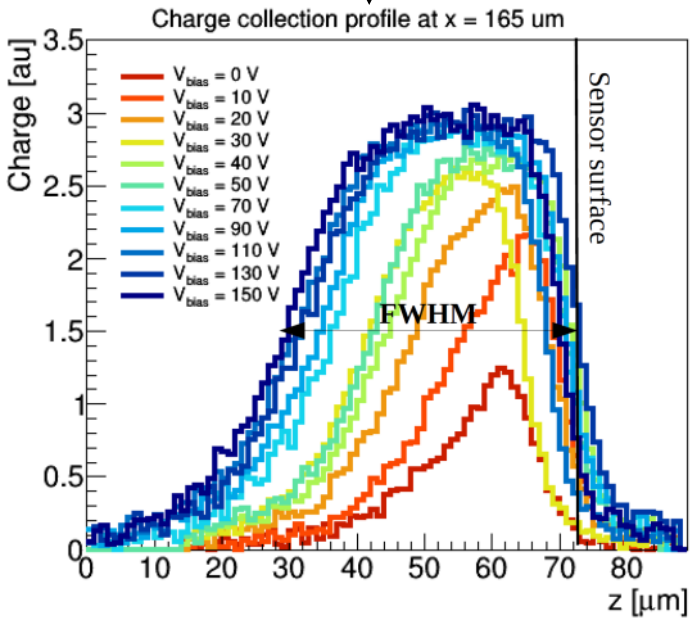
HV-CMOS

- H35Demo: AMS technology
  - Test of different pixel matrix types
  - Test structures on chip for R&D



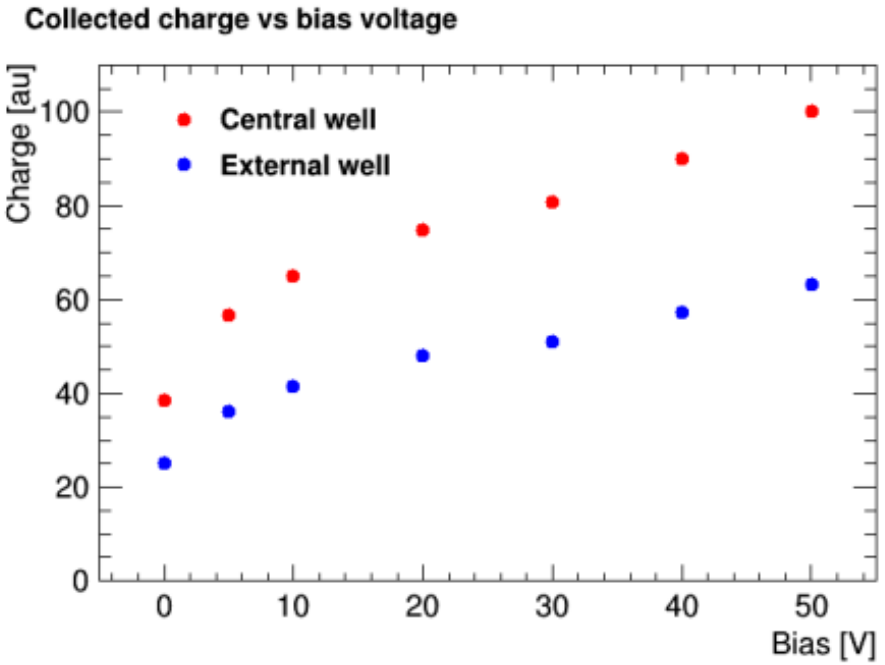
Edge TCT



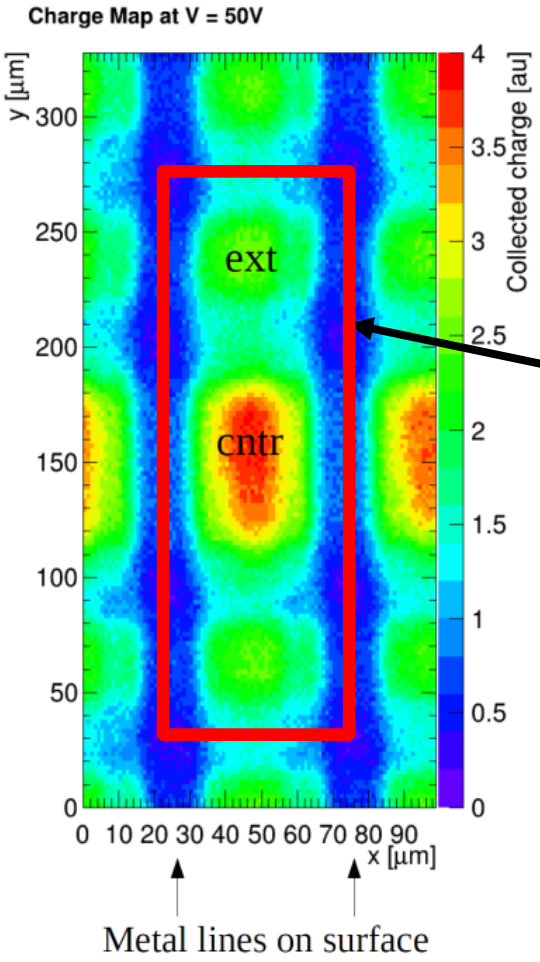


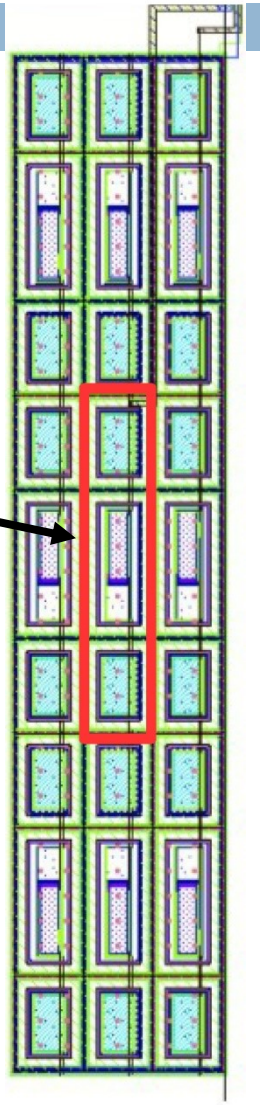
Pictures from E. Cavallaro; 28th RD50 workshop

HV-CMOS



Top TCT





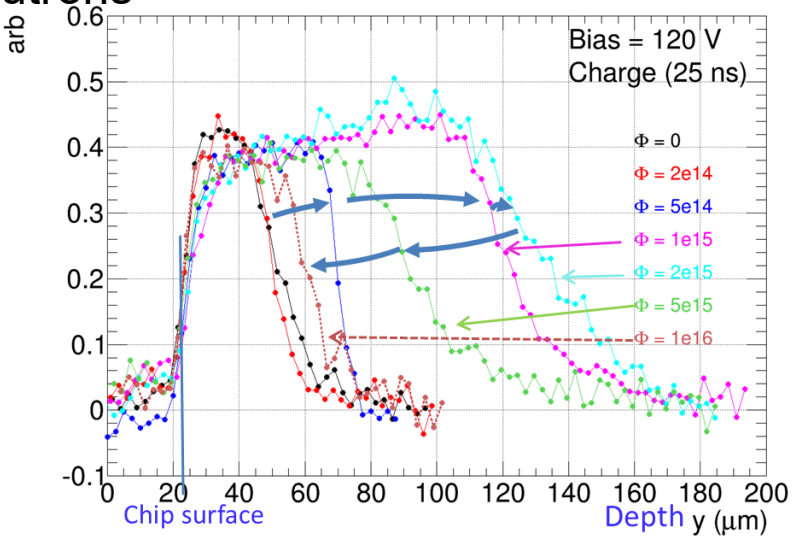
Measurements show 1 test cell:

- Central: DNWELL with nMOS/pMOS
- External: smaller DNWELL at each side

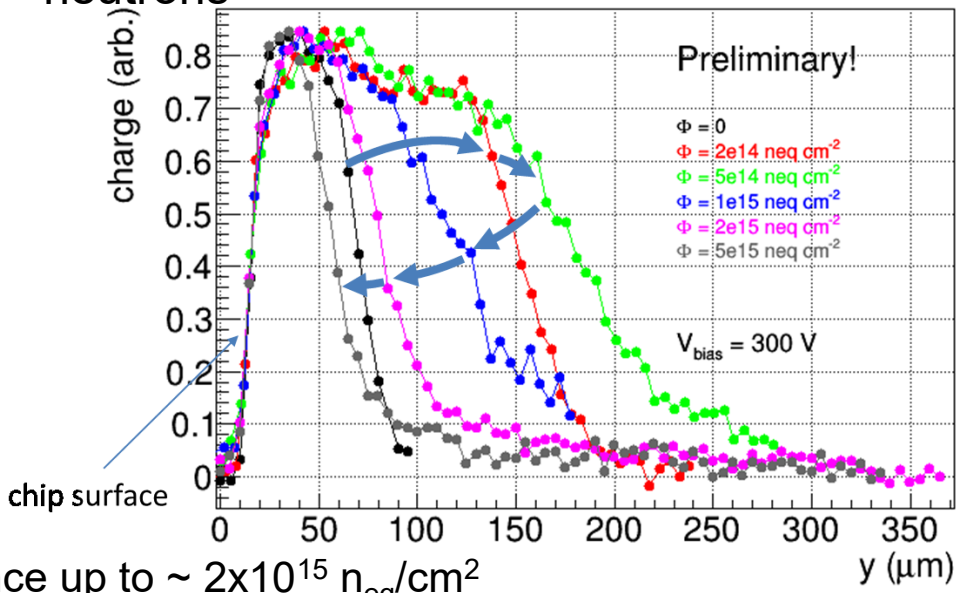
Pictures from E. Cavallaro; 28th RD50 workshop

HV-CMOS

AMS sensor, irradiated with reactor neutrons



XFAB sensor, irradiated with reactor neutrons

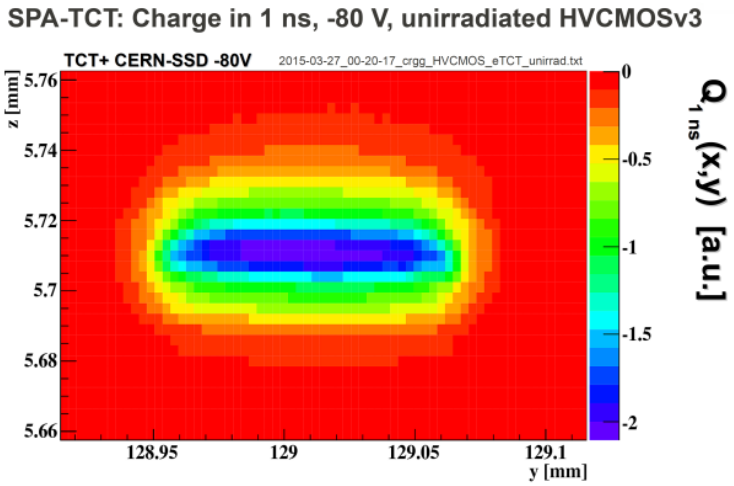


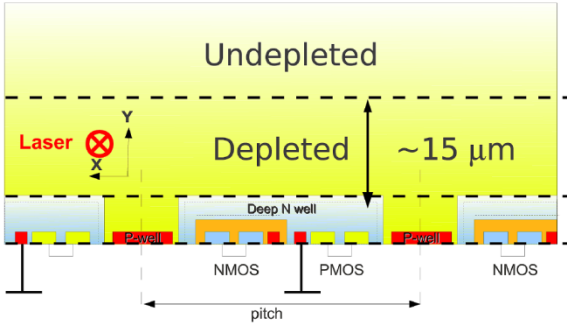
- charge collection width increases with fluence up to ~ 2×10^{15} n_{eq}/cm^2
  - ➔ initial acceptor removal
- charge collection width falls with fluences above ~ 2×10^{15} n_{eq}/cm^2
  - ➔ initial acceptor removal finished, space charge concentration increases with irradiation
- at 1×10^{16} n_{eq}/cm^2: *AMS* charge collection width still larger than before irradiation; *XFAB* narrower; *LFoundry* shows small increase at low fluences ($1\text{-}5 \times 10^{13}$ n_{eq}/cm^2) with the following decrease

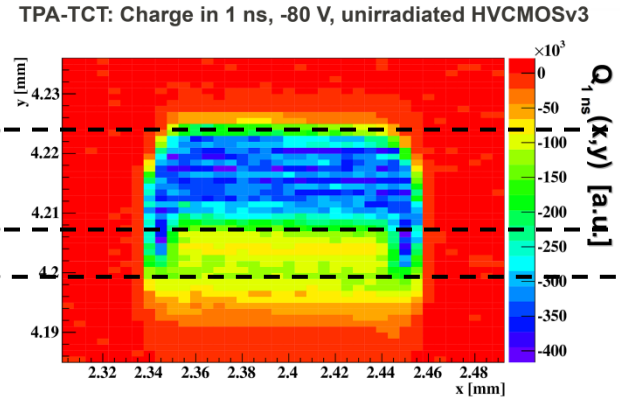
I. Mandić, 28th RD50 workshop; B. Hiti , ITK week (12-16/09/2016)
G. Kramberger et al., 2016 JINST 11 P04007

HV-CMOS TPA-TCT

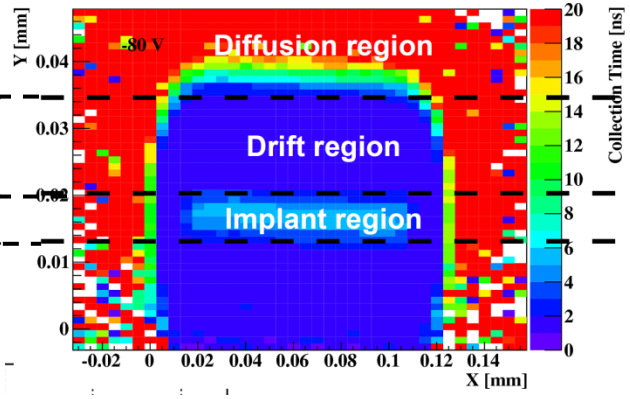
- Compare measurements of unirradiated HV-CMOS devices with standard SPA-TCT and TPA-TCT
  - DNW without embedded NMOS or PMOS
  - With SPA-TCT substructure not visible







Collected charge map



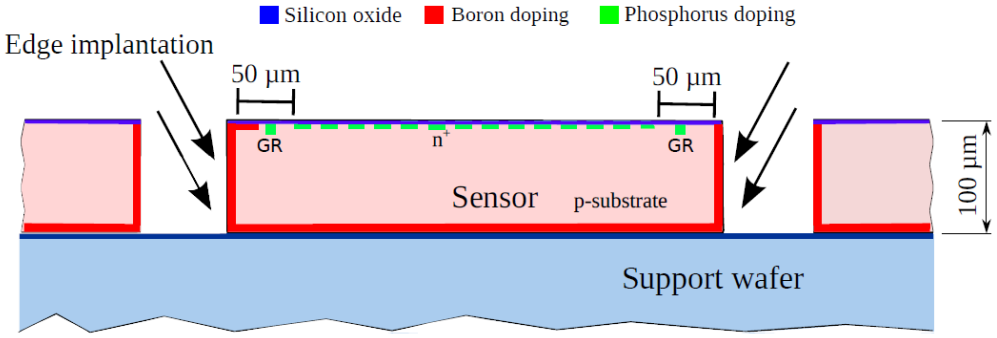
Collection time map

Time laps between begin and end of signal

M. Fernandez; 28th RD50 workshop

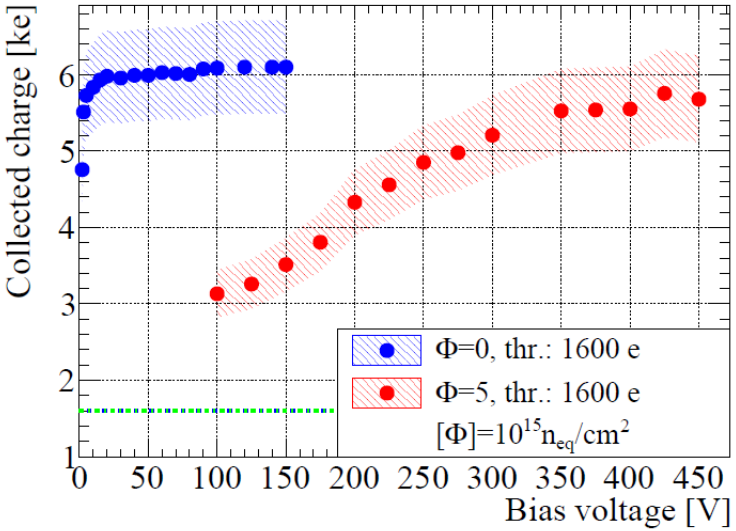
Slim/Active Edge

- Slim edge: reduce ~1mm wide inactive region
  - Important for tiled sensor systems like staves
- Active edge: pixel sensors with a width 100-200 µm
  - Trenches doped by four-quadrant implantation
  - different edge designs under investigation



S. Terzo; 23th RD50 workshop

100µm thick; 5x10^{15} n_{eq}/cm^2;
FE-I4; 125µm active edge

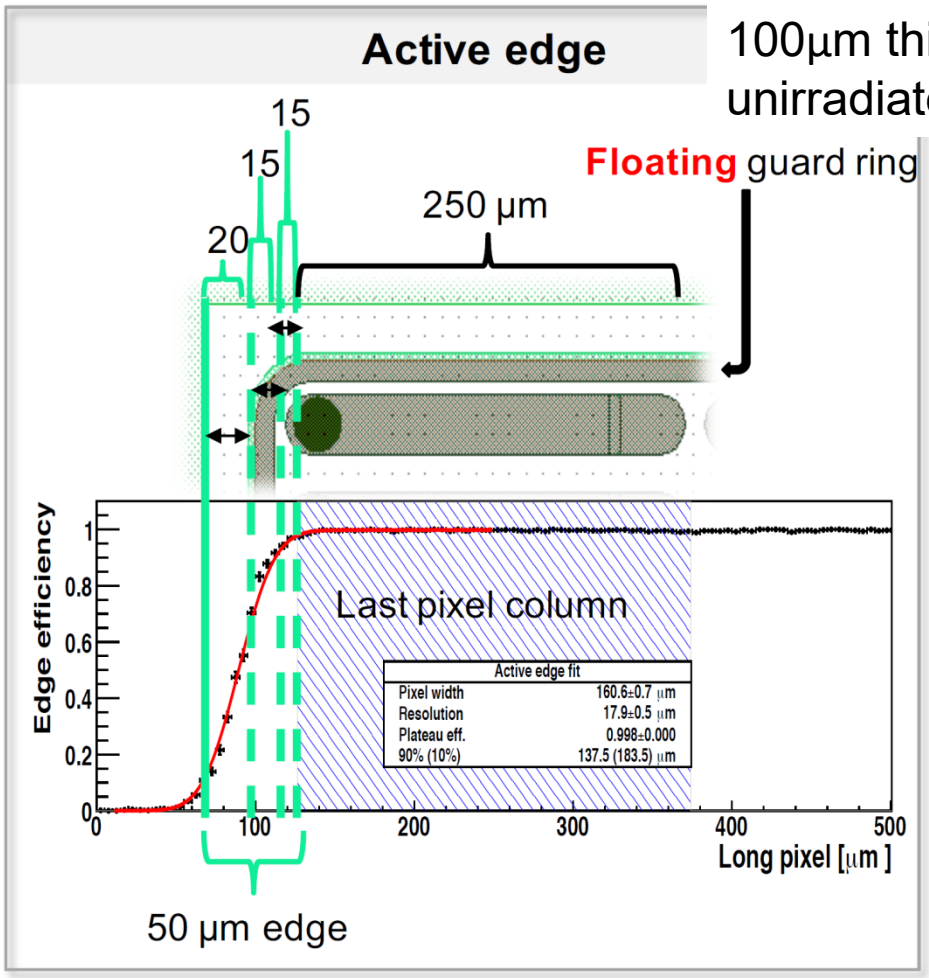


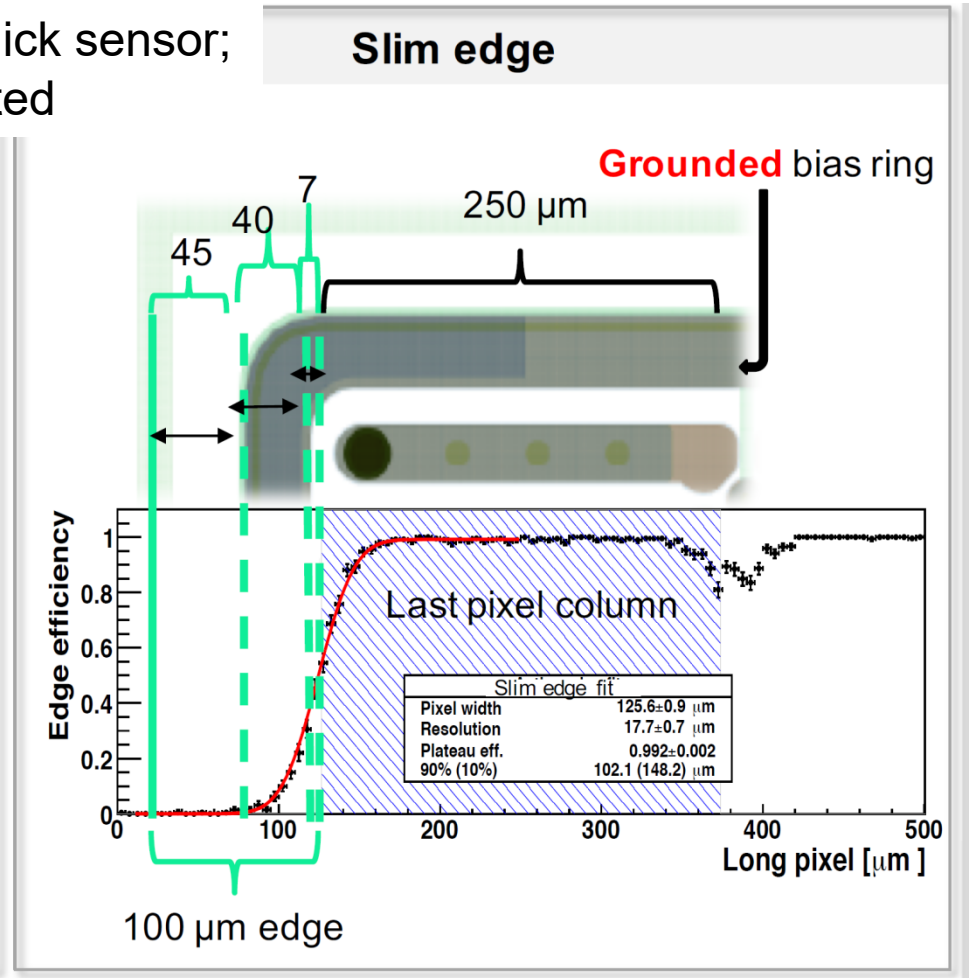
CCE: (95±13)% at 425V

B. Paschen; 25th RD50 workshop

Slim/Active Edge

100µm thick sensor; unirradiated





Smearing due to resolution of ~18µm

Summary

Within the CERN RD50 collaboration several new semiconductor detector structures are investigated for their radiation hardness

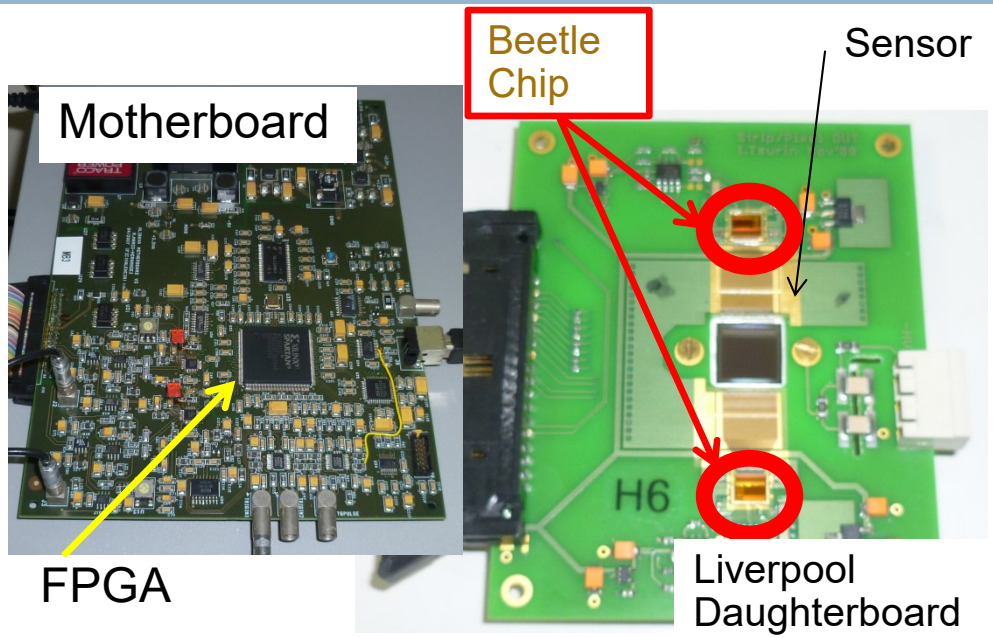
- 3D sensors
  - Benefit from the decoupling of the electrode distance form the active sensor thickness
  - Can be used as pixel or strip detectors
  - First sensors used in ATLAS IBL and AFP
- HV-CMOS
  - Utilizing the industrial CMOS standard to produce semiconductor detectors (pixel) for high energy particle physics experiments
  - First test with different technologies are very promising
- LGAD
  - Create sensors with built in amplification layer
- Slim/active edge devices to reduce the amount of dead space at the sensor edges are under investigation

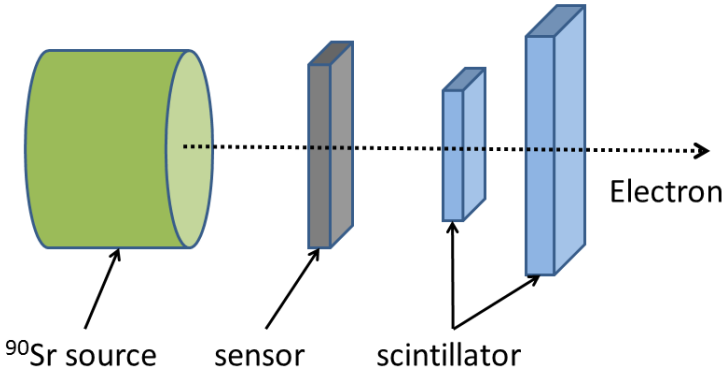
Backup

ALiBaVa System

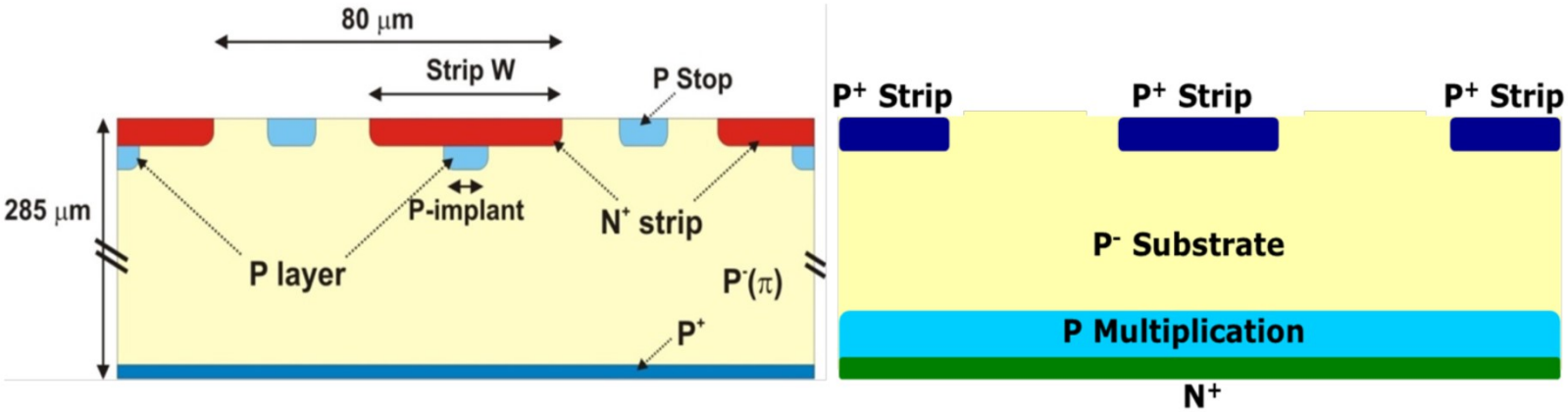
Use ALiBaVa system for charge collection measurements

- Beetle chip (ASIC) for analogue readout (signal amplification and shaping)
- MIP's from ^{90}Sr source to perform charge collection measurements
- Scintillators for triggering





inverse LGAD



N on P microStrip

LGAD

P on P microStrip

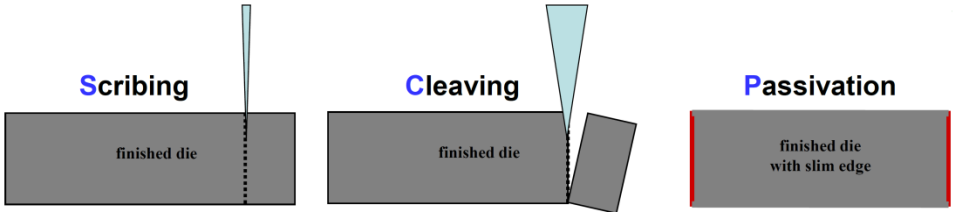
iLGAD

S. Hidalgo; 27th RD50 workshop

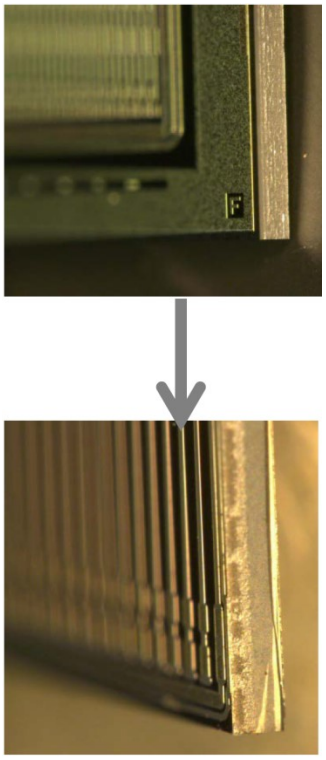
Slim/Active Edge

- Slim edge: reduce ~1mm wide inactive region
  - Important for tiled sensor systems like staves
- One method is SCP, done at SCIPP:

Scribing → Cleaving → Passivation



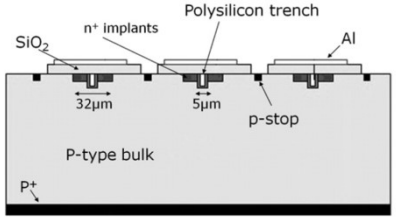
- SCP provides good performance due to low defect density on the side walls
  - A possible modification could be Cut → Damage Removal → Passivation

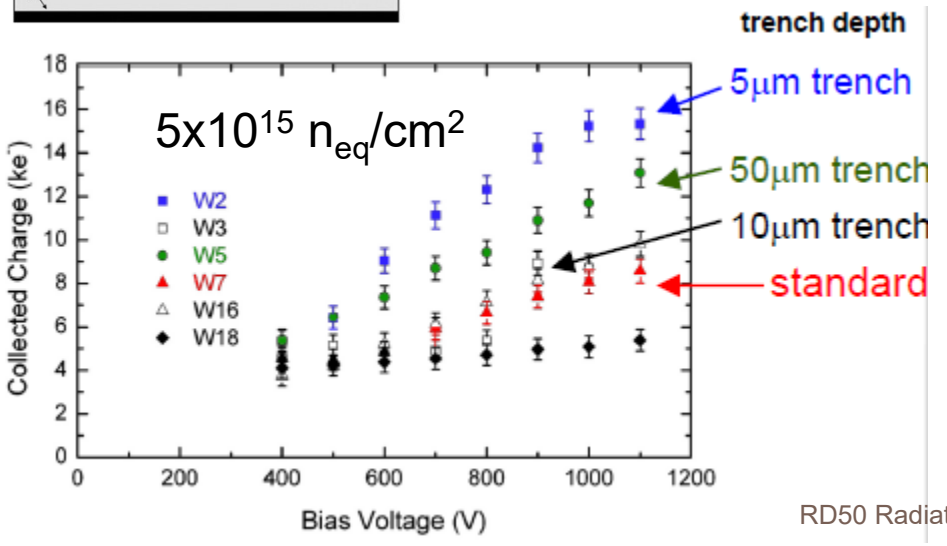


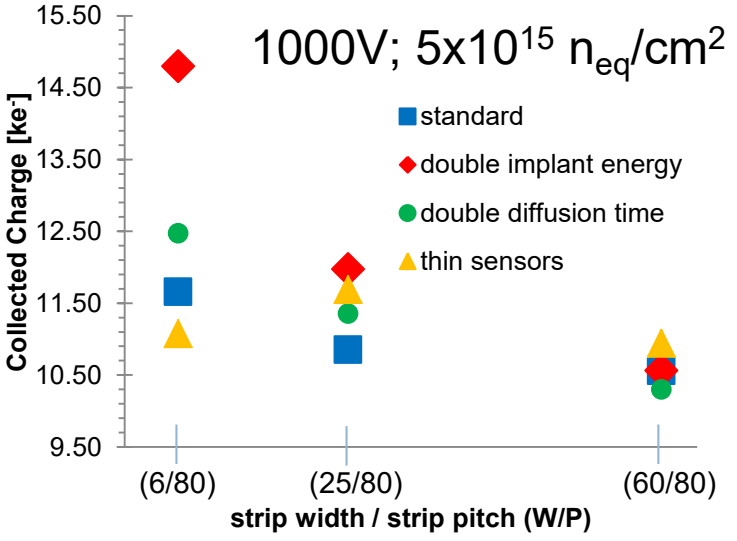
V. Fadeyev; 23rd RD50 workshop

Charge Multiplication

- Charge multiplication observed in sensors after irradiation to 2-5x10^{15} n_{eq}/cm^2
  - Irradiation leads to high negative space charge in detector bulk
    → increase of the electric filed close to n-type strips
    → impact ionization
  - Exploit charge multiplication by junction and device engineering







S. Wonsak; PSD10

G. Casse et al; NIM-A 699 (2013) p 9-13