WP7 (NA6): Advanced hybrid pixel detectors

Anna Macchiolo (UZH), Iván Vila (CSIC-IFCA)

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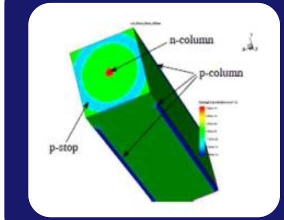
Outline

- Brief introduction to WP7:
  - Deliverables & milestones
- Production runs
  - Planar, 3D and LGADs
- Characterizations results.
- TCAD benchmarking: data vs simulation.

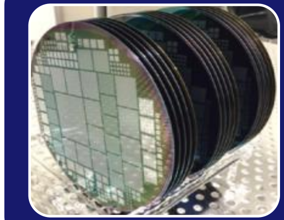
WP7 in a nutshell

Radiation-tolerant **vertexing** & **timing** sensors



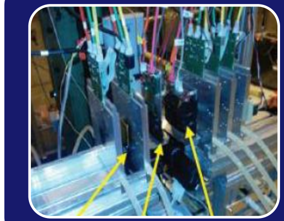
Device Simulation

- Layout optimization.
- Radiation damage modeling
- Optimization signal multiplication structures.



Sensor manufacturing

- Development & improvement of manufacturing processes for planar, 3D and LGAD devices.
- MPWR for thinned 3D and slim/active edge planar.



Detector performance assessment

- Hybrid thin planar & 3D pixels for HL-LHC environment.
- Very small size and thin pixel sensors for CLIC.
- Low Gain Avalanche Detectors for timing and tracking

CERN
FONDAZIONE BRUNO KESSLER
INFN Istituto Nazionale di Fisica Nucleare
Planck-Institut für Physik (Werner-Heisenberg-Institut)
MANCHESTER 1824 The University of Manchester
CSIC
LAL
LPNHE PARIS
UH
UNIVERSIDAD DE SEVILLA

WP7 Deliverables

Device simulation

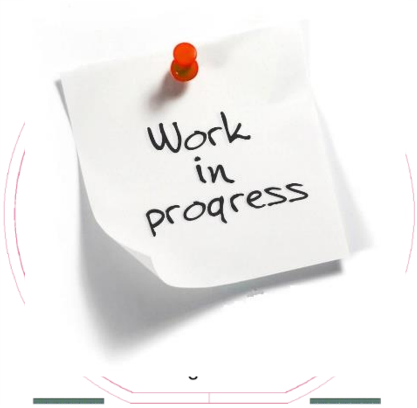
Device characterization

Deliverable	ponsible oup	Month due
D7.1 Simulation of 3D pixel sensor cells ✔	INFN	M18 (OCT 2016)
D7.2 Simulation active edge ✔	CERN	M18 (OCT 2016)
D7.3 LGAD simulation ✔	INFN	M18 (OCT 2016)
D7.4 TCAD model radiation damag	INFN	M46 **SEP** 019)
D7.5 Wafer Layout MPW run WP7 ✔	CSIC	M30 (NOV 2017)
D7.6 Initial pixel characterization ✔	UNIMAN	M24 (APRIL 2017)
D7.7 Final pixel characterization	MPG-MPP	M46 **SEP** 019)
D7.8 LGAD characterization	INFN	M46 **SEP** 019)

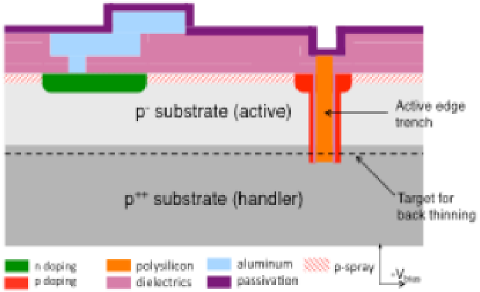
WP7 Milestones

Milestones	sponsible Group	Month due
MS29 Validation and release of TCAD simulation ✔	INFN	M16 (AUG 2016)
MS49 Workshop on 3D and planar sensors ✔	FBK	M24 (APR 2017)
MS51 Workshop on LGAD characterization ✔	INFN	M24 (APR 2017)
MS50 Technological choice on L or thick ✔	CSIC	M24 (APR 2017)
MS81 Test beam campaign for 3D a s	MPG-MPP	M36 (APR 2018)
MS87 Common MPW runs completion	CSIC	M42 (DEC 2018)
MS97 Validation TCAD radiation damage n ith data comparison	INFN	M46 **SEP** 2019)

Four Manufacturing runs

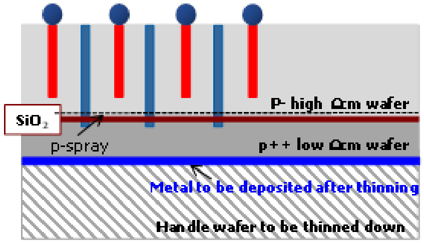


ACTIVE EDGE
PLANAR PIXEL



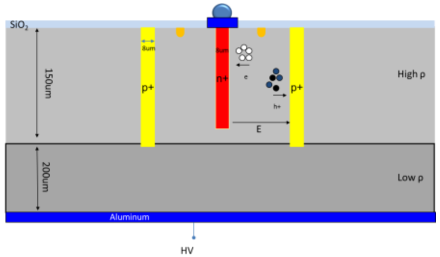
FONDAZIONE
BRUNO KESSLER

Single-Sided
SoI & SiSi **3D PIXELS**



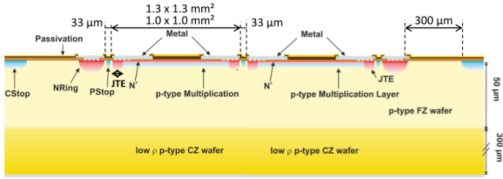
Centre Nacional de Microelectrònica IMB

Single-Sided
SiSi **3D PIXELS**



Centre Nacional de Microelectrònica IMB

Extra-Thin
SiSi **LGADs**

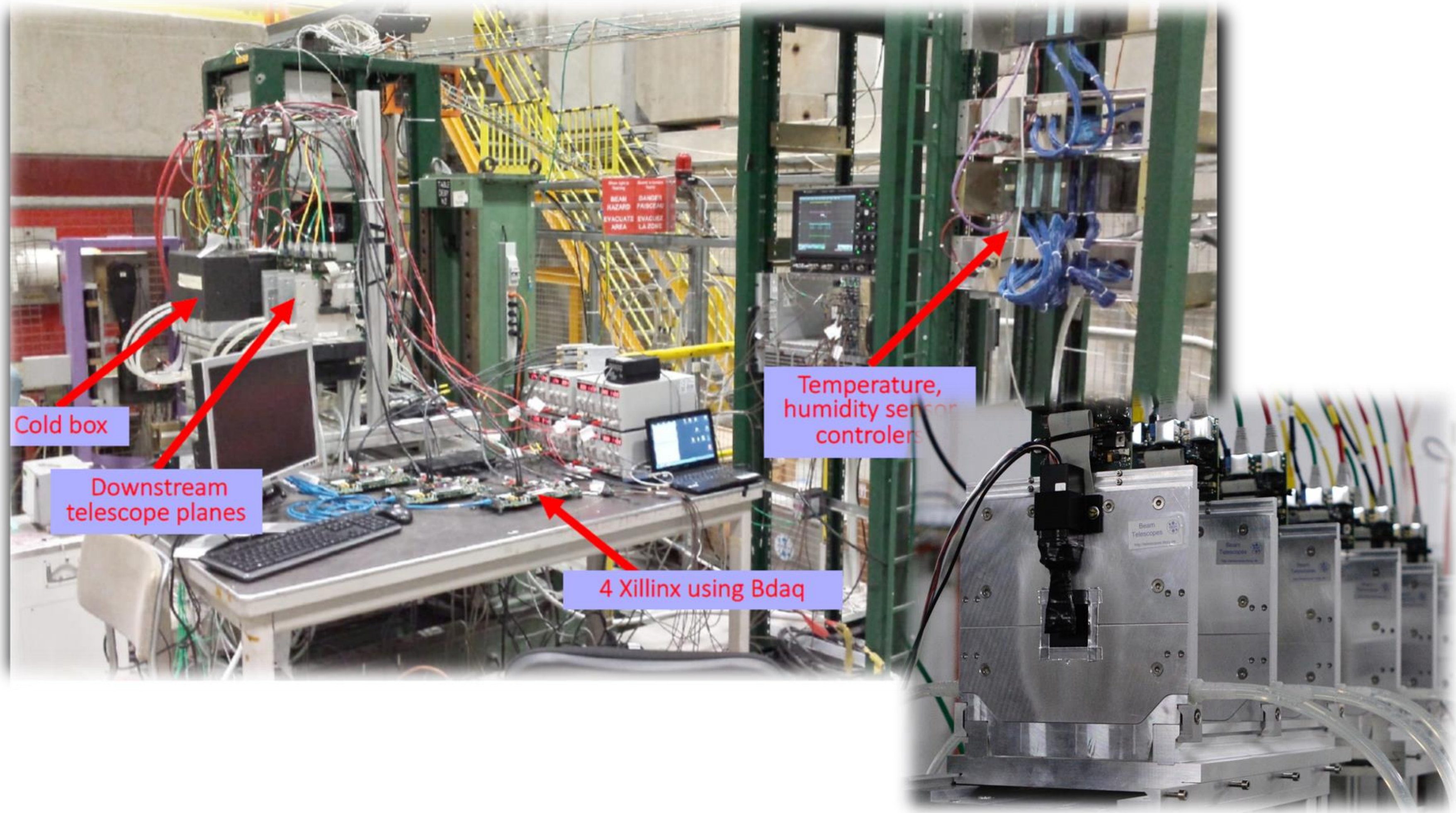


Sensor Characterization and simulation at a glance

TECNOLOGY/ MANUFACTURER	DELIVERED	PRE-IRRAD CHARACTERIZATION	POST-IRRAD CARACTERIZATION	TECHNOLOGY/ RADIATION DAMAGE SIMULATION
3D SiSi (FBK)	YES	COMPLETED (CCE, HIT EFFICIENCY, HIT RESOLUTION, CROSS TALK)	COMPLETED (1e16 n_e/cm^2)	YES
3D SiSi (CNM)	YES	COMPLETED (CCE, HIT EFFICIENCY, HIT RESOLUTION, CROSS TALK)	IN PROGRESS (samples under irradiation)	YES
THIN LGAD (CNM)	YES	COMPLETED (TIMING, GAIN)	COMPLETED (1e15 n_e/cm^2)	YES
AE PLANAR (FBK)	IN PROGRESS(*)	NA	NA	YES

(*) The strong delay on the delivery of the required wafers in combination with the shutdown of the FBK production line for technological improvements and the recent coronavirus crisis lock down prevented the completion of this run. **As fallback, the assessment of AE and planar sensors coming from previous FBK prototyping runs was done.**

Power users of EUDET/AIDA saga telescopes


Cold box

Downstream telescope planes

4 Xillinx using Bdaq

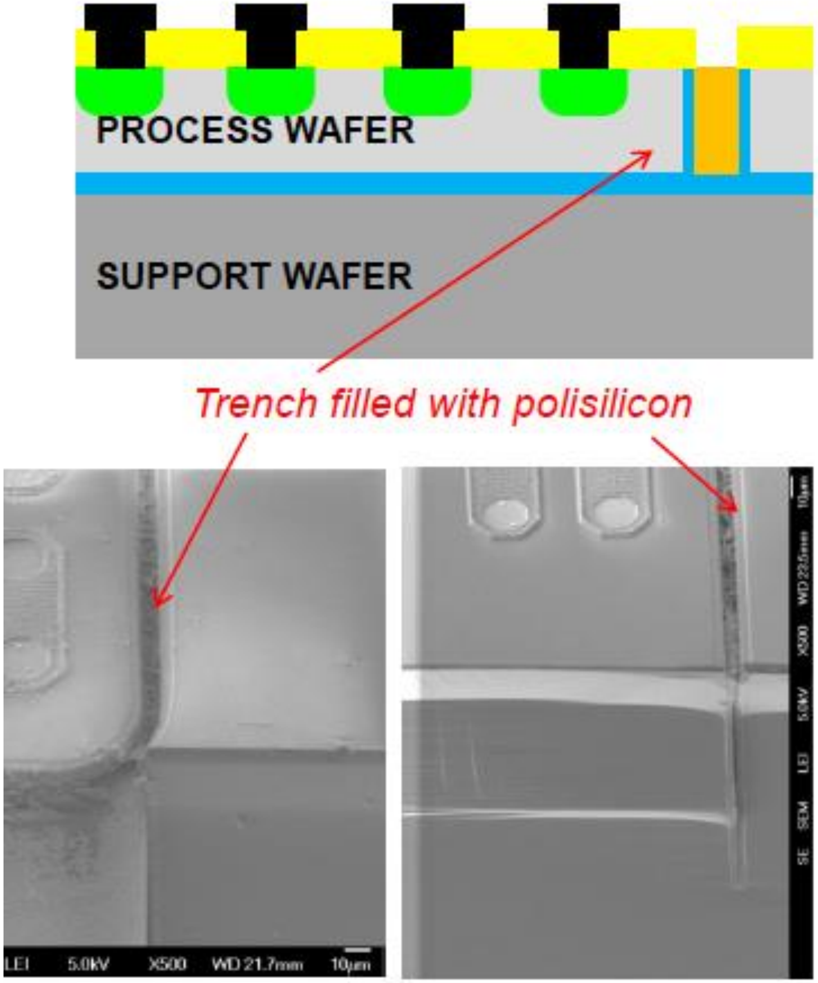
Temperature, humidity sensor controlers

Small-cell AE Planar pixels

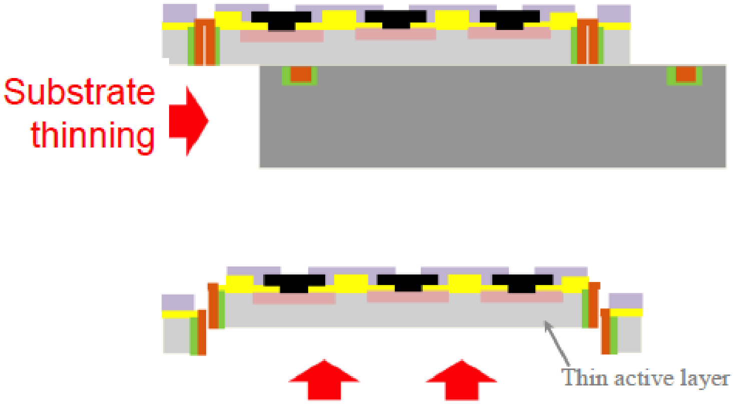
Strong delay in the SOI wafer delivery and closure of FBK facilities during lockdown

→ Delay in production, completion now foreseen in Summer 2020

- Continuous trenches - Width < 10 um
- SOI wafers 50 (x2), 100 (x5) and 150(x5) µm thick
- Poly-silicon filling, multi-geometries (# of GR)
- Substrates thinning leads to structure separation

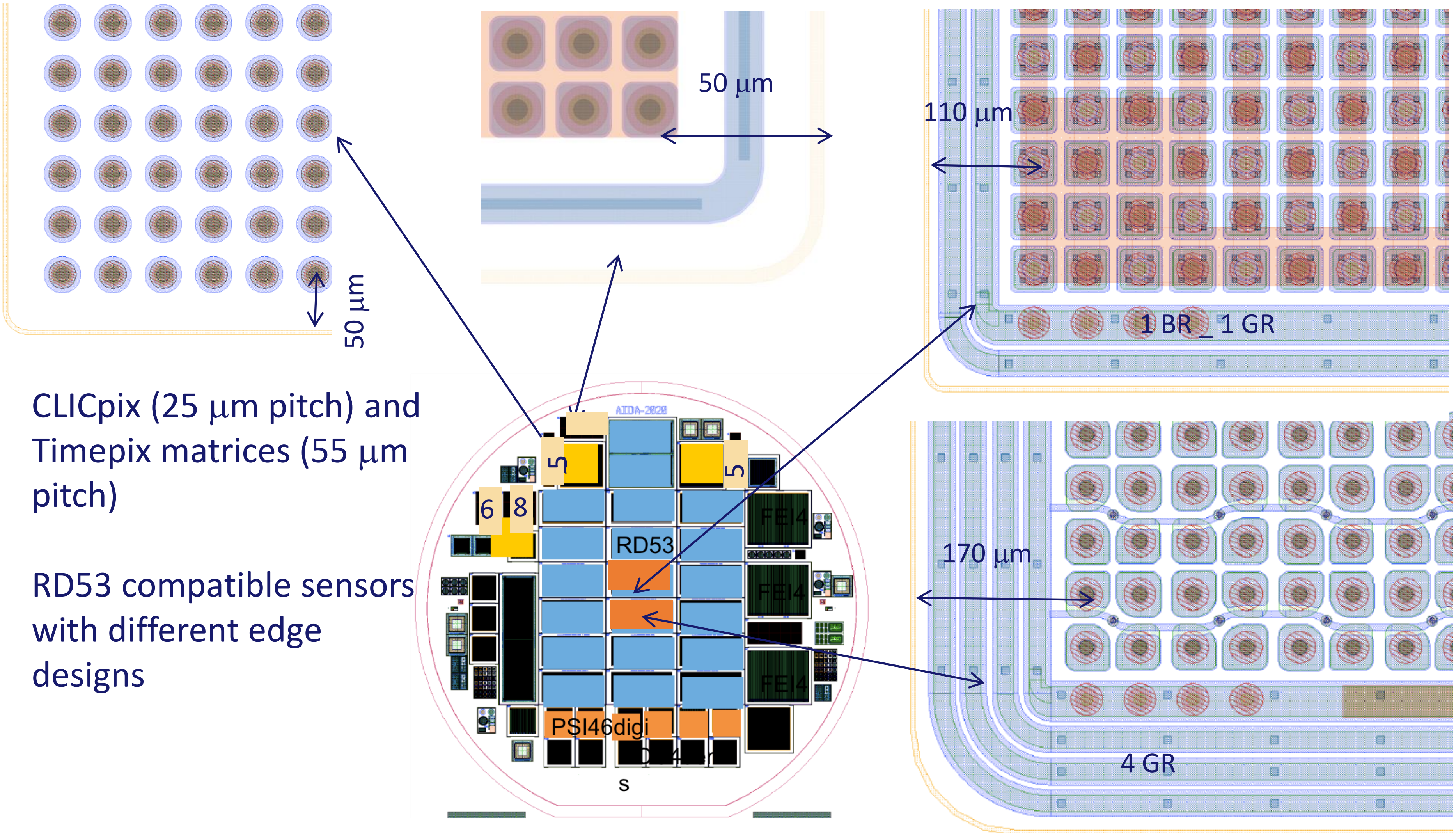


Trench filled with polisilicon



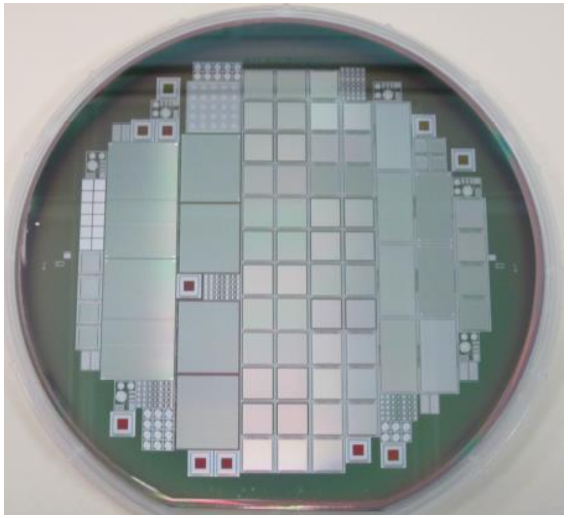
Device separation along the trenches

Active edge production layout



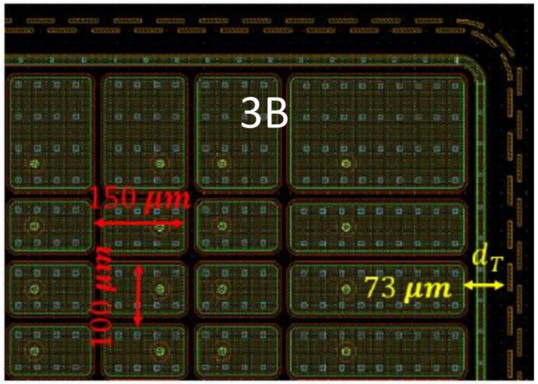
- CLICpix (25 µm pitch) and Timepix matrices (55 µm pitch)
- RD53 compatible sensors with different edge designs

FBK staggered trench run: PSI46dig sensors

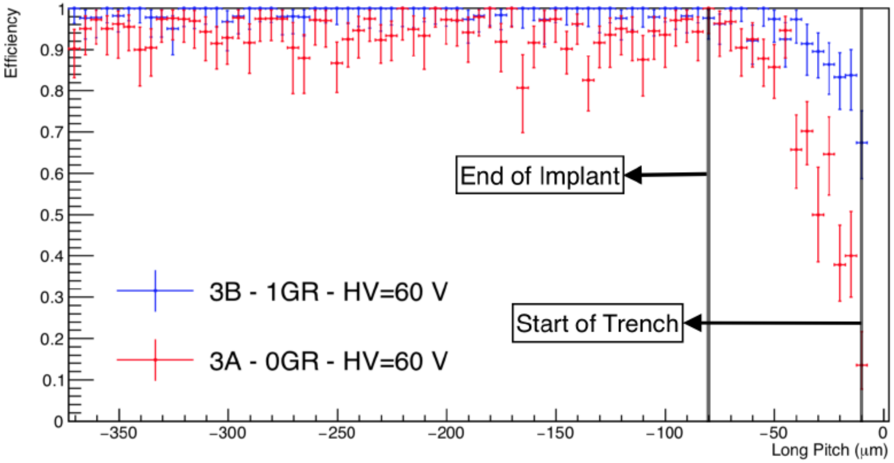


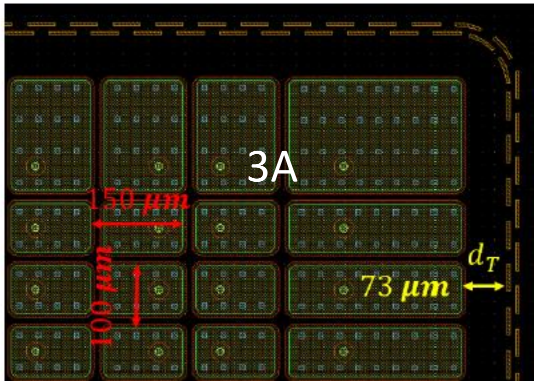
- 130 and 130 μm thickness
- SOI and Si-Si wafers
- CMS PSI46dig, ATLAS FE-I4, RD53A, CLICPix2 sensors

PSI46dig modules

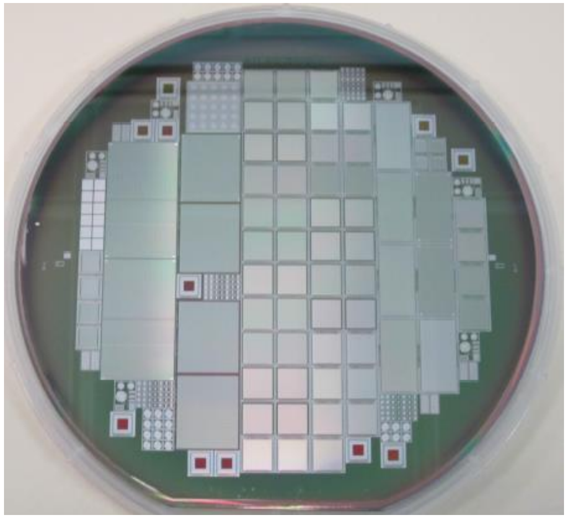


(b) Modulo 3B.

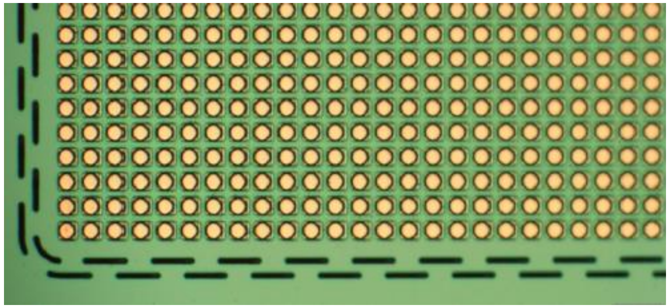




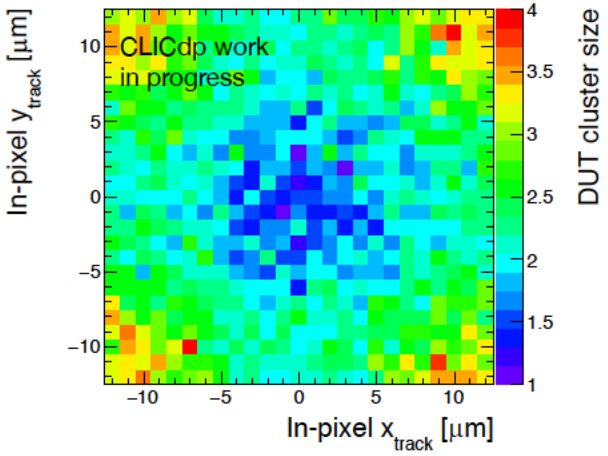
FBK staggered trench run: CLICpix2 sensors

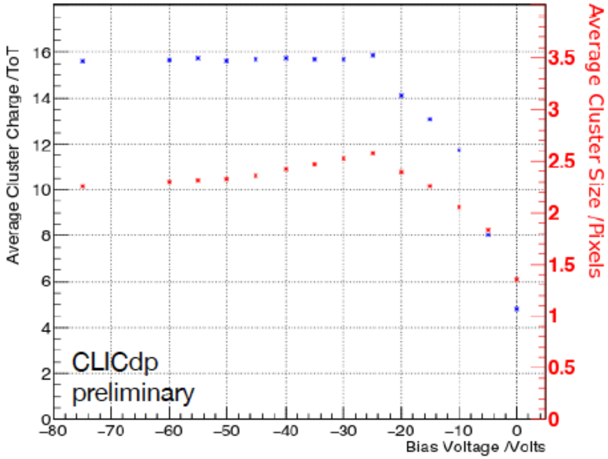


CLICpix2 modules



- Sensors compatible with the CLICpix2 chip in 65 nm CMOS
- 128 x 128 pixels
- Pitch = 25 x 25 µm

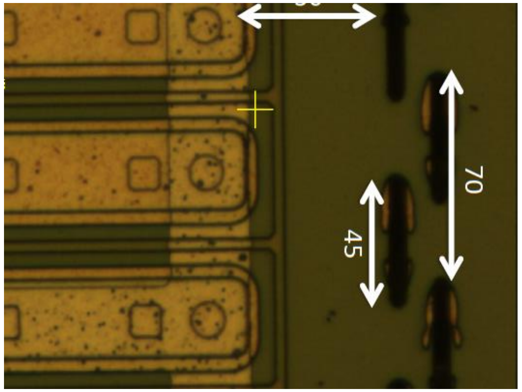


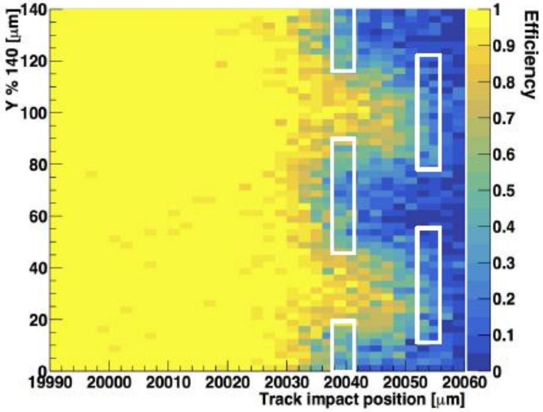


- DUT positional resolution = ~3.8 µm for 130 µm sensor thanks to charge sharing
- Hit detection eff.=99.97%

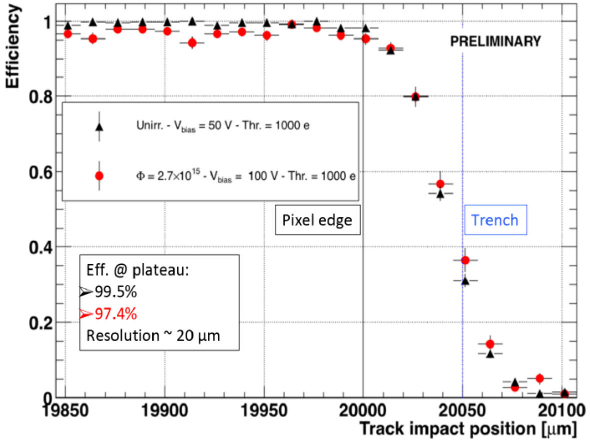
FBK staggered trench run: FE-I4 sensors

FE-I4 sensors, 130 μm thick, with staggered trenches before irradiation





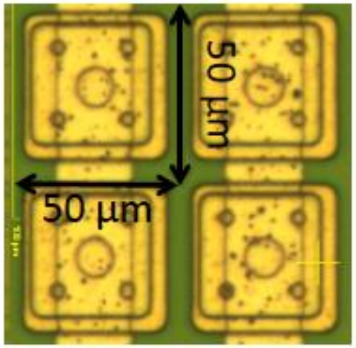
- No GR structure
- Efficiency follow staggered trench pattern
- Efficiency higher than 50% up to 44 μm from last pixel (total width=50 μm)



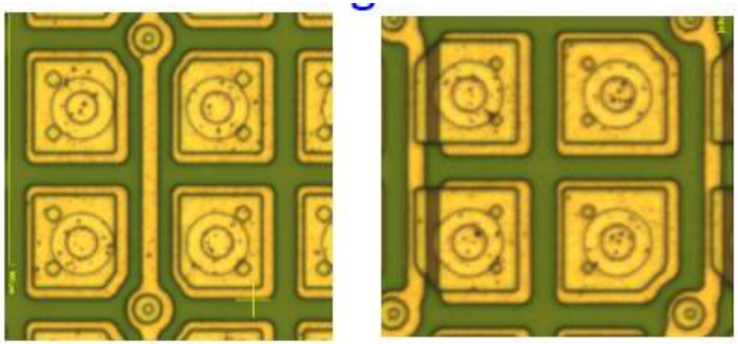
- Irradiation at KIT 2.7×10^{15} n_{eq}/cm^2
- Efficiency comparable to unirradiated performance: >80% up to 25 μm from the last pixels

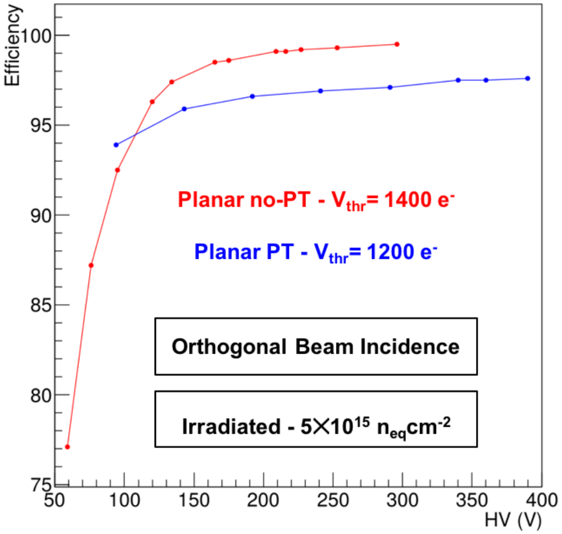
Characterization of FBK irradiated RD53A planar sensors

No PT



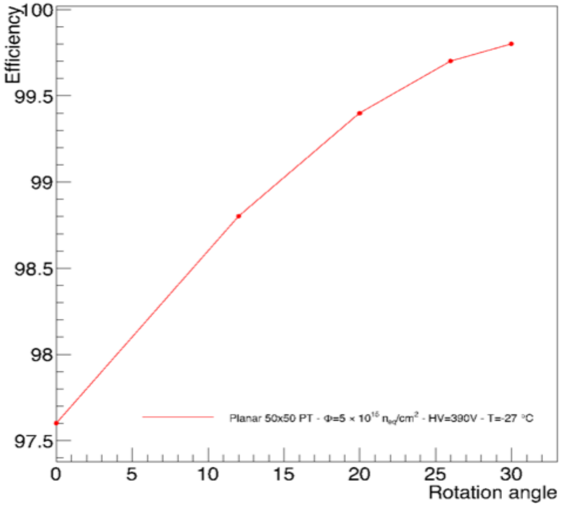
Biasing structures In the two versions: straight and wiggled metal lines





Efficiency>99.5% at 300V for no PT case at perpendicular incidence

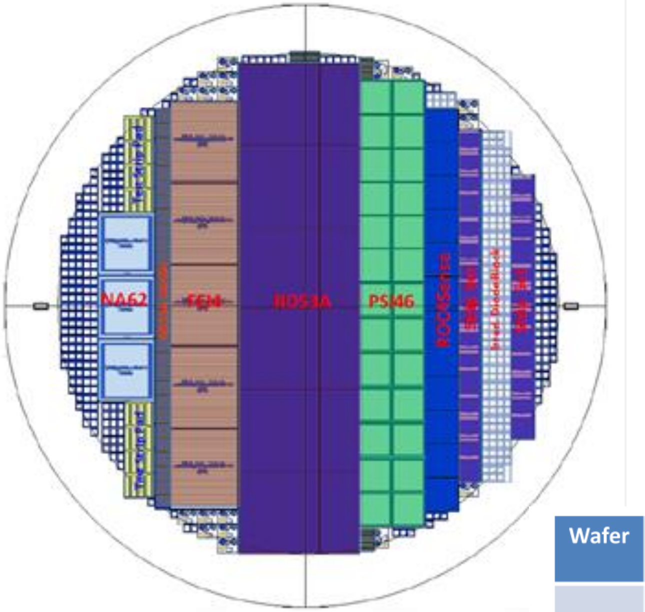
Efficiency recovered for PT case alreadt at 15^{O} tilt



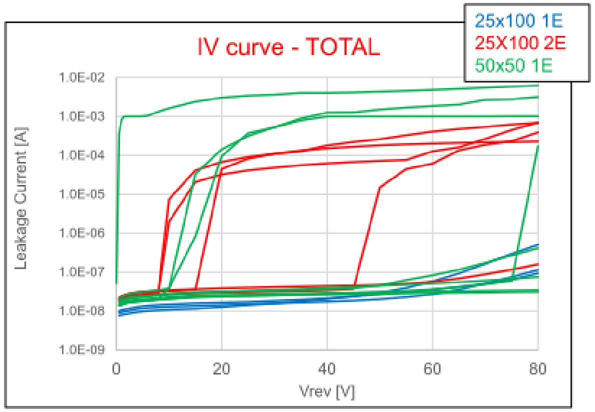
Small –cell 3D pixels

Run completed in February 2018
Characterization of irradiated and not-irradiated structures well under way

Ok - pixel cell 50x50 – 1E
Ok - pixel cell 25x100 - 1E
Problem - pixel cell 25x100-2E



- R4S
  - 50 x 50 (1E)
  - 25 x 100 (1E and 2E)
- RD53A
  - 50 x 50 (1E) 8X
  - 25 x 100 (1E) 3X
  - 25x100 (2E) 7X
- CHIPIX65
  - 50 x 50 (1E and 2E)
  - 25 x 100 (1E and 2E)



Wafer	Where		Good/Acceptable RD53A sensors		
		Total	50x50	25x100-1E	25x100-2E
W2	Leonardo (Italy)	8	6	2	0
W5		8	6	1	1
W3	IZM (Germany)	9+1	5	3	1+1
W79		9	7	2	0
W91		6	3	2+1	0

Issue with 25x100-2E understood, too short distance between ohmic column & routing metal

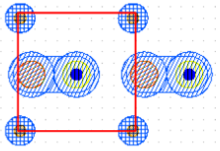
⇒ Fabrication with **stepper photolithography** to increase precision and **re-design of the metal routing.**

After irradiation: 50x50 μm^2

Efficiency 1x1 pixel cell maps and profiles over X direction

Normal incidence.

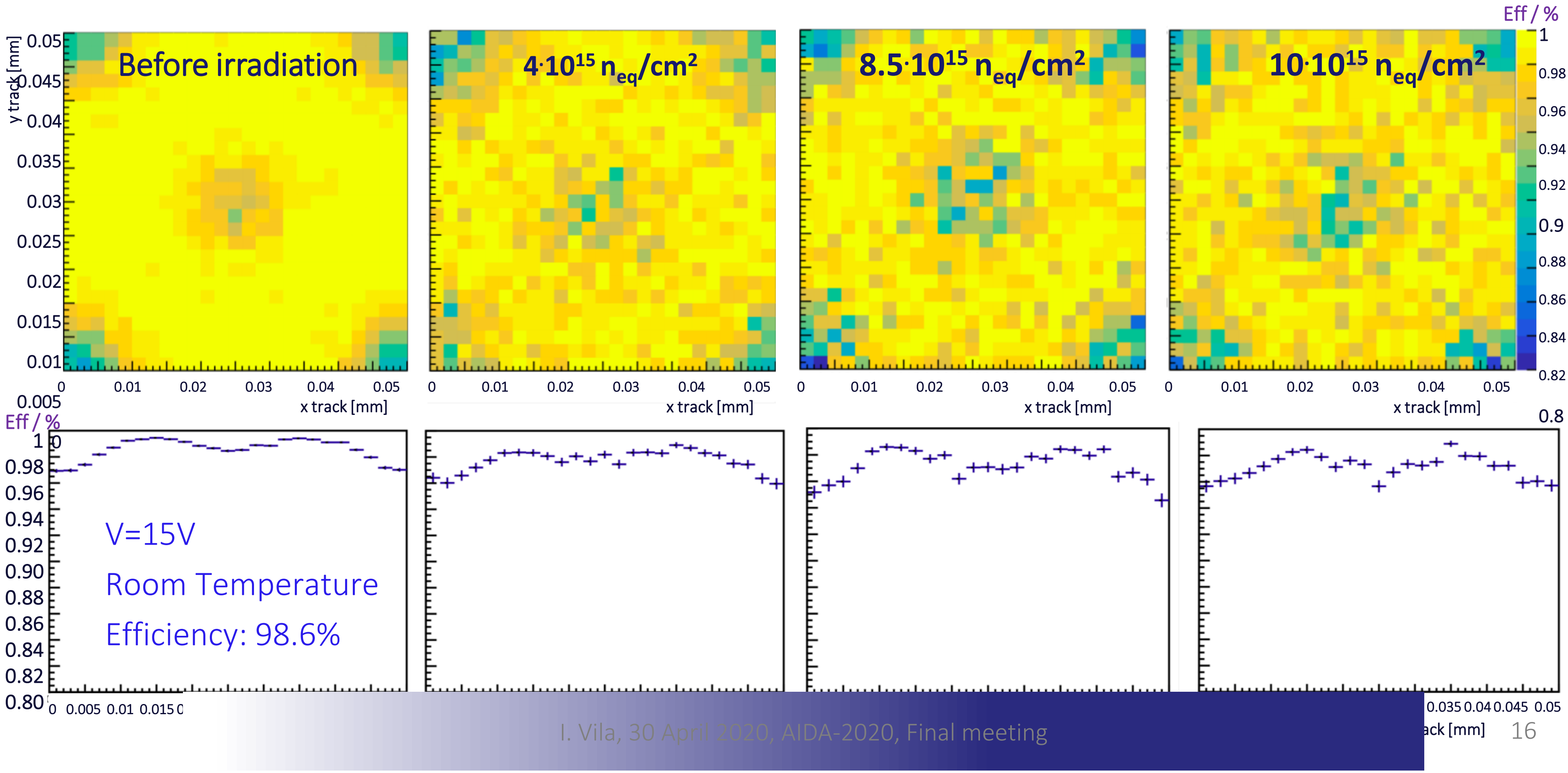
V=141V. T=-36°C



Eff = 97.68%

Eff = 97.20%

Eff = 97.11%



Before irradiation

$4\cdot10^{15}$ n_{eq}/cm^2

$8.5\cdot10^{15}$ n_{eq}/cm^2

$10\cdot10^{15}$ n_{eq}/cm^2

V=15V

Room Temperature

Efficiency: 98.6%

After irradiation: 25x100 μm^2

- Demonstration of the radiation tolerance of the rectangular geometry with one collecting electrode

Non-irradiated

$4.0\ 10^{15}$ n_{eq}/cm^2

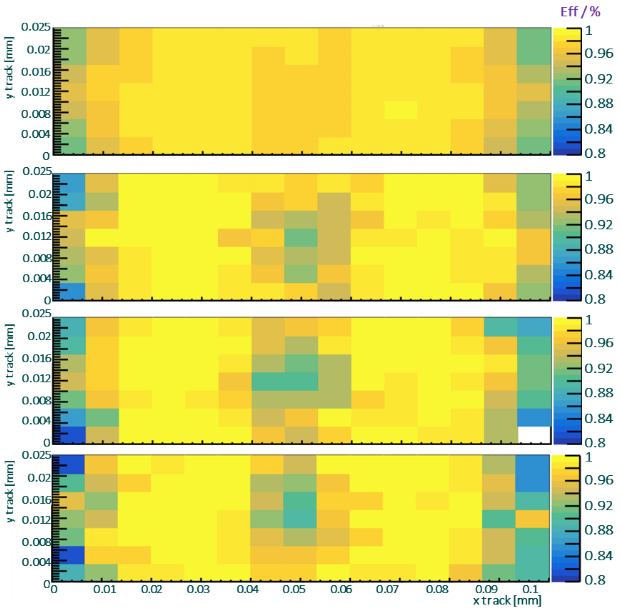
Eff = 97.35%

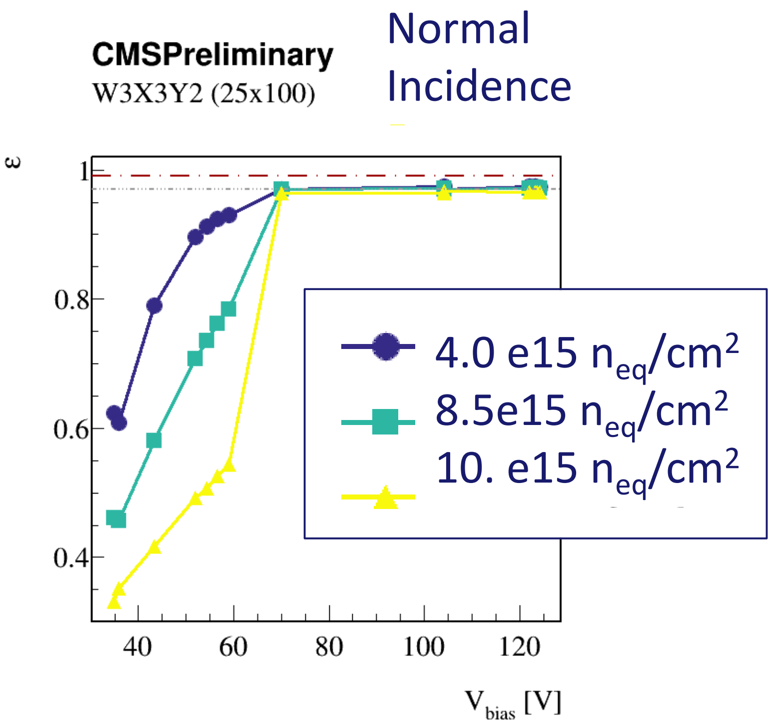
$8.5\ 10^{15}$ n_{eq}/cm^2

Eff = 96.35%

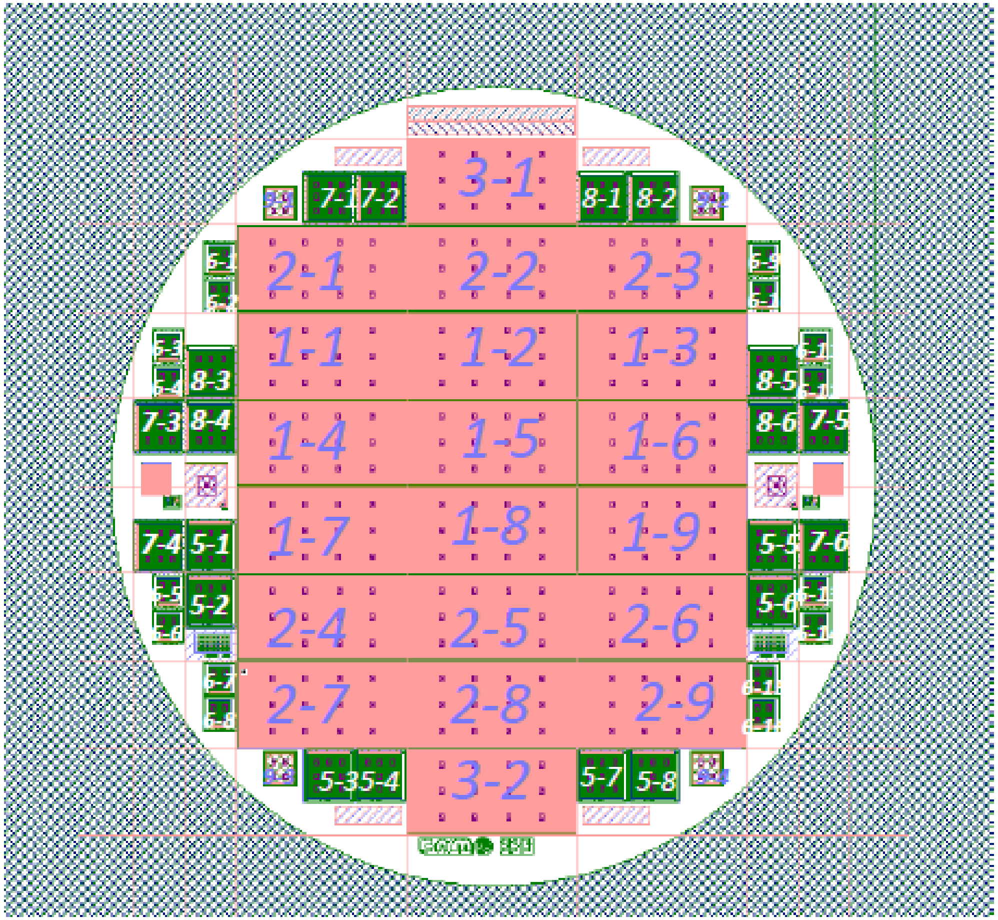
$10\ 10^{15}$ n_{eq}/cm^2

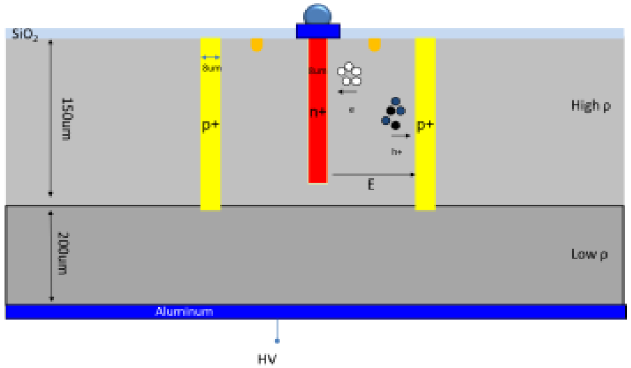
Eff = 96.36%





AIDA-2020 3D run at CNM



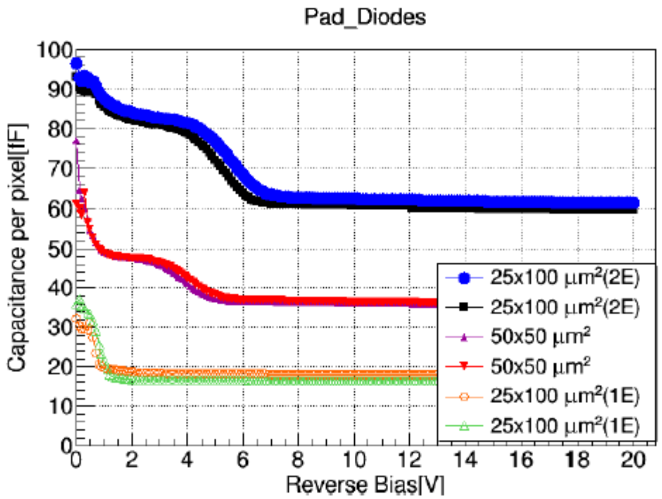


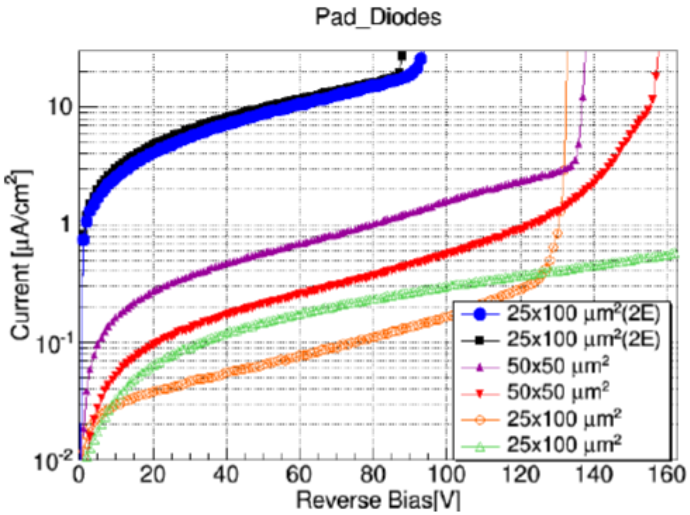
Run completed in February 2019, seven wafers + one additional wafer for process control.

- Si-on-Si 4” wafers (150 mm + 200 mm)
- Single-sided 3D sensors pixels with RD53A layout.
- Etched columns: 8 um diameter, 120 um length.

AIDA-2020 3D run at CNM

- Very low capacitance for 25x100 (1E) geometry (below 20fF)
- The leakage current per pixel below 25pA/pixel for 50x50 µm^2 and 25x100 µm^2 (1E) geometries at 80 Volts (x10 for the 2E geometry)





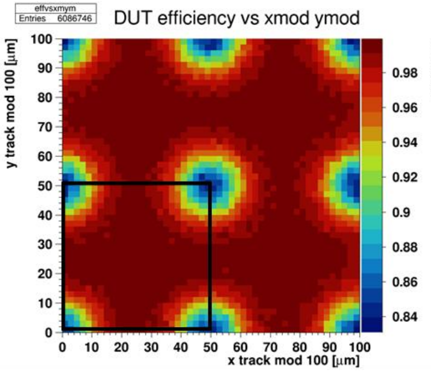
Pixel cell 50x50:	79%	(50/63)
Pixel cell 25x110(1E):	50%	(7/14)
Pixel cell 25x110(2E):	6%	(4/63)

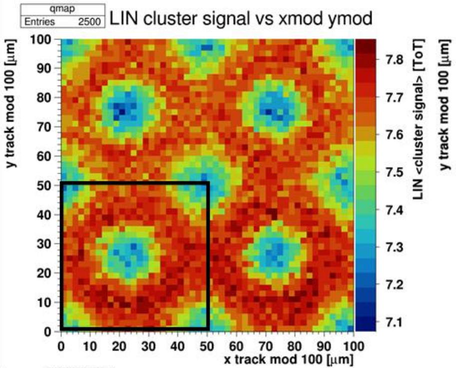
Yield Summary

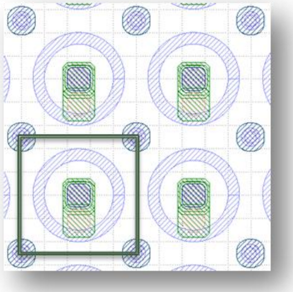
AIDA-2020 3D run at CNM

September/October 2019 test beam at DESY

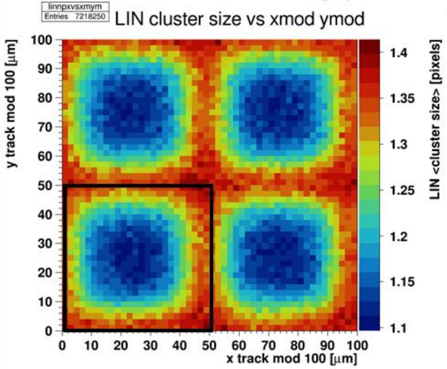
50x50 um2



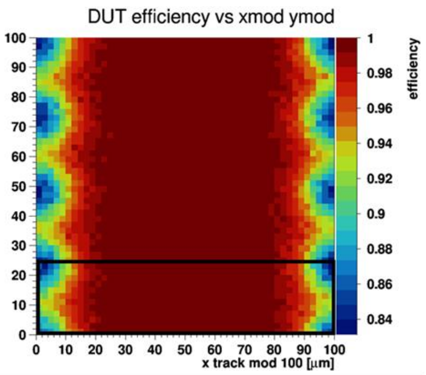


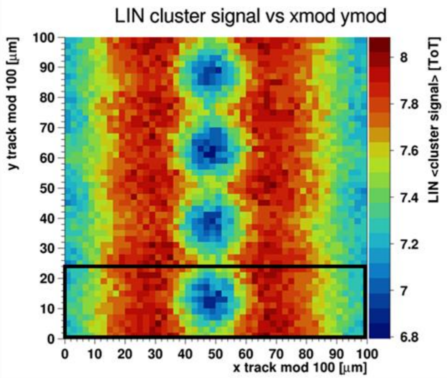


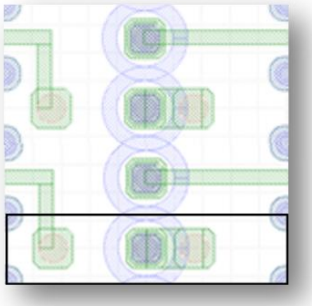
Normal incidence. -5V



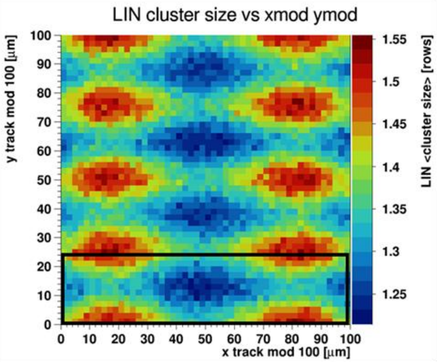
25x100 um2





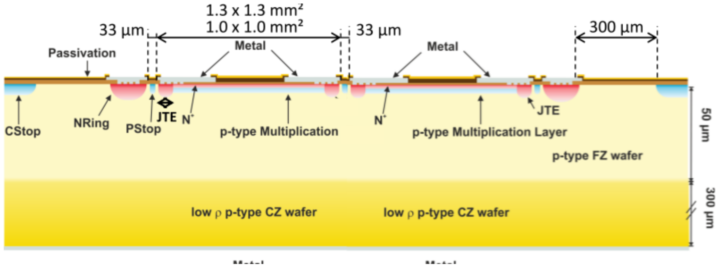


Normal incidence. -20V



Very-thin LGADs

- Delivered in Sept. 2018
- Lay-out agreed with CMS and Atlas MIP timing detector groups.
- Two RD targets:
  - **Increase the radiation tolerance** by reducing the active thickness up to 35um (mitigation of double-junction induced gain reduction)
  - **Increase the gain fill factor** by reducing the width of JTE of the LGADs (reducing the inter-pad no-gain area)

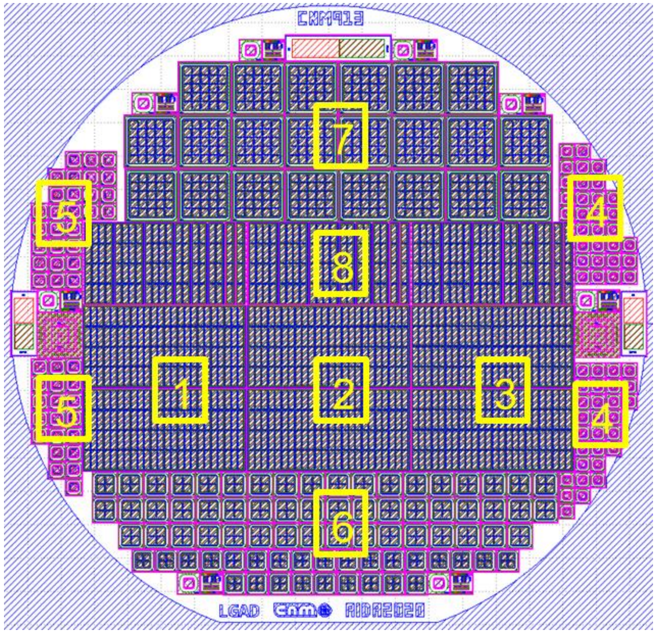


6x CMS_3x1_4x24_JTE

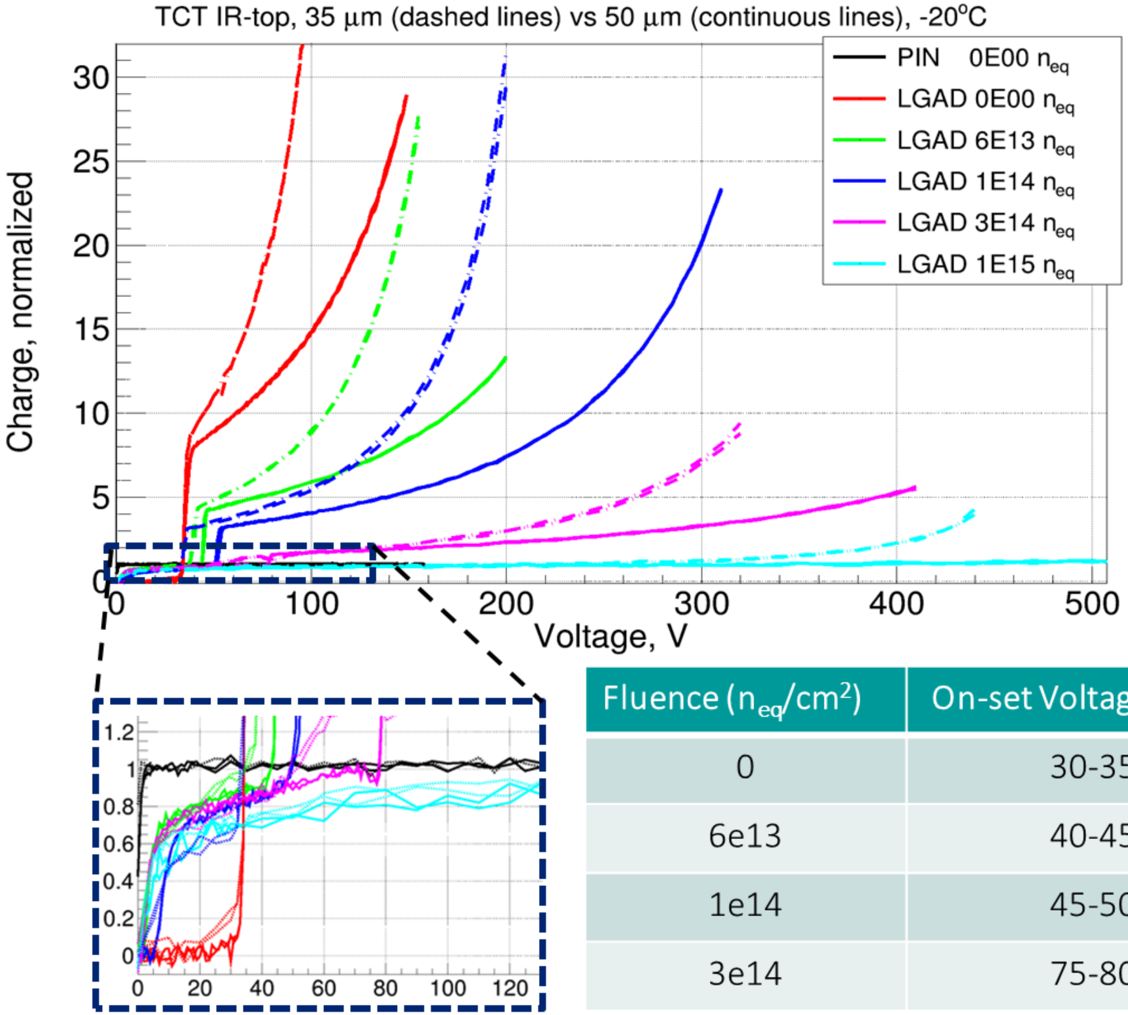
2x: JTE = 5 µm (1)
2x: JTE = 10 µm (2)
2x: JTE = 15 µm (3)

22x **HGTD_S_5x5_BUMPADS** (7)

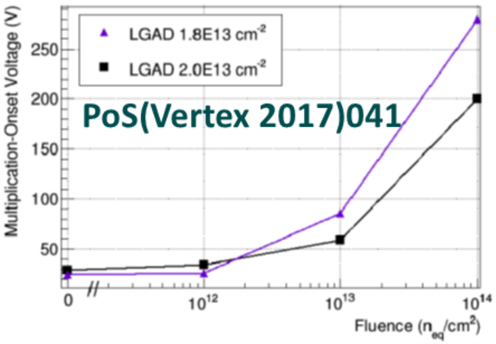
ATLAS HGTD Array 5x5 (1.3 x 1.3 mm2)



TCT Characterization: Charge vs. Bias Voltage

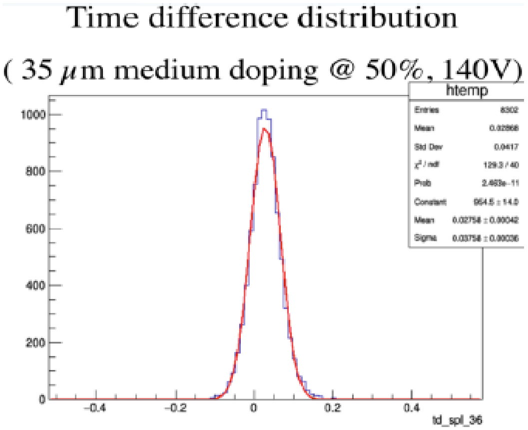


Positive shift of gain offset observed in [S. Otero et al., PoS(Vertex 2017)041] on 300µm thick sensors.

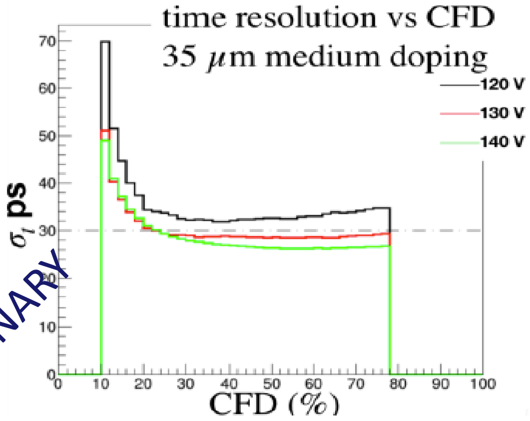


Fluence (n_{eq}/cm^2)	On-set Voltage (Volts)	CV Voltage@maximum
0	30-35	35(CV foot)
6e13	40-45	35
1e14	45-50	40
3e14	75-80	70

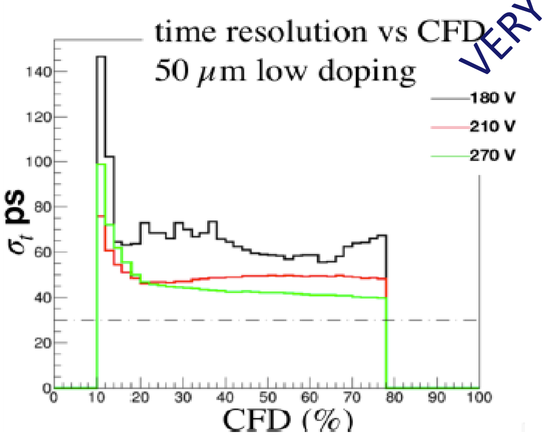
Timing resoluting (β source)

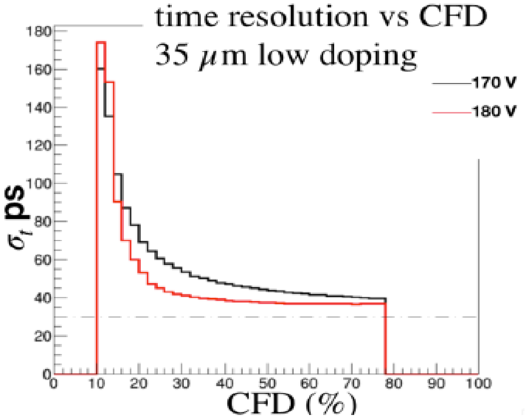

Time difference distribution

(35 μm medium doping @ 50%, 140V)

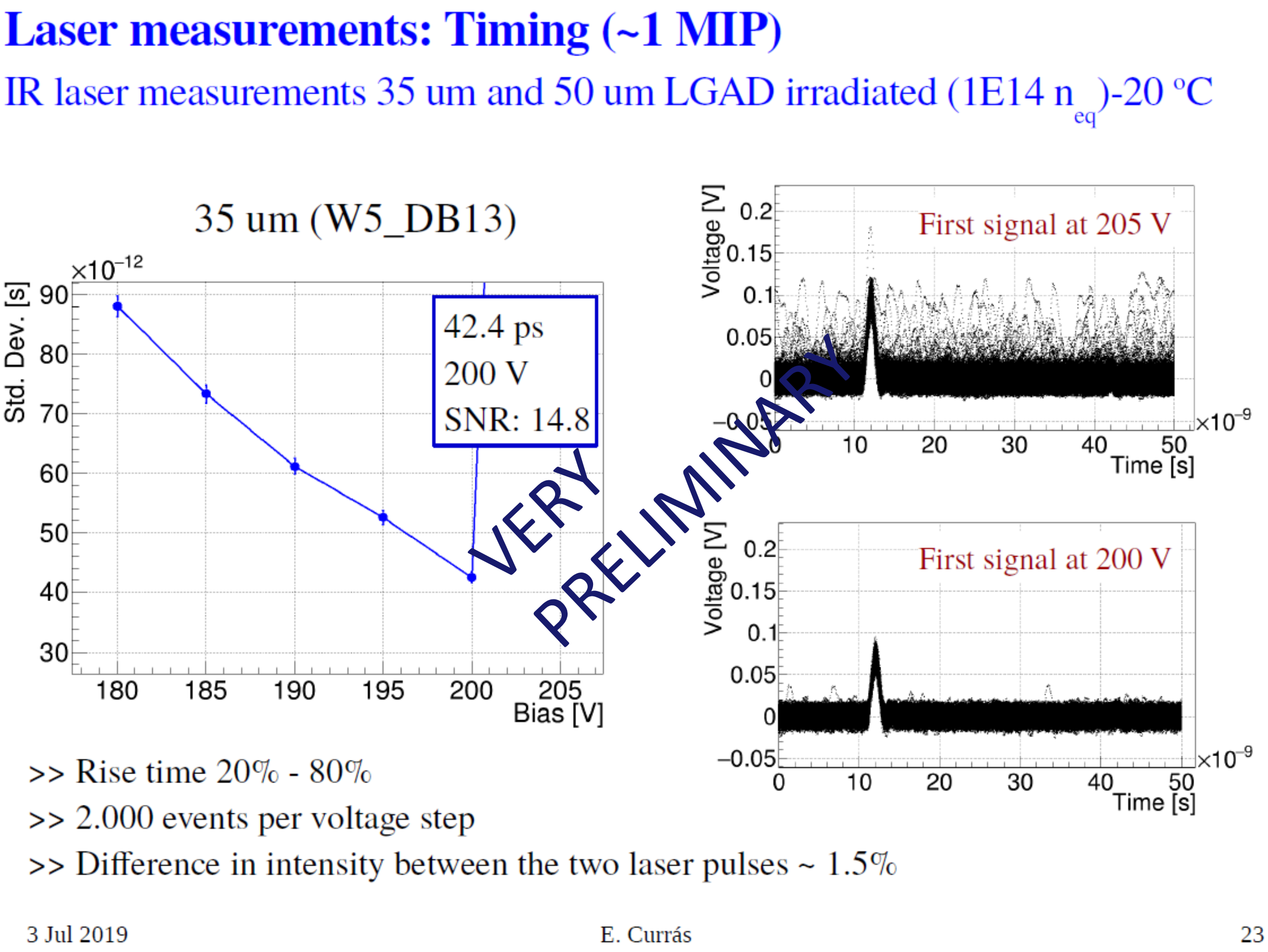

time resolution vs CFD
35 μm medium doping

VERY PRELIMINARY


time resolution vs CFD
50 μm low doping


time resolution vs CFD
35 μm low doping

Timing and operation stability (pop noise)



Laser measurements: Timing (~1 MIP)

IR laser measurements 35 um and 50 um LGAD irradiated (1E14 n_{eq})-20 °C

- \>> Rise time 20% - 80%
- \>> 2.000 events per voltage step
- \>> Difference in intensity between the two laser pulses ~ 1.5%

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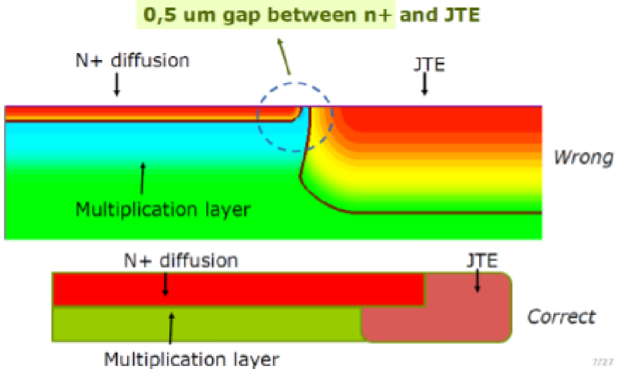
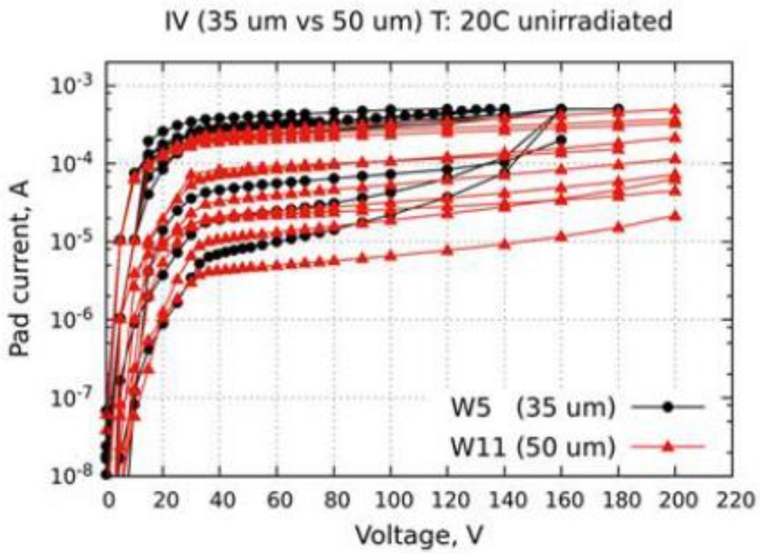
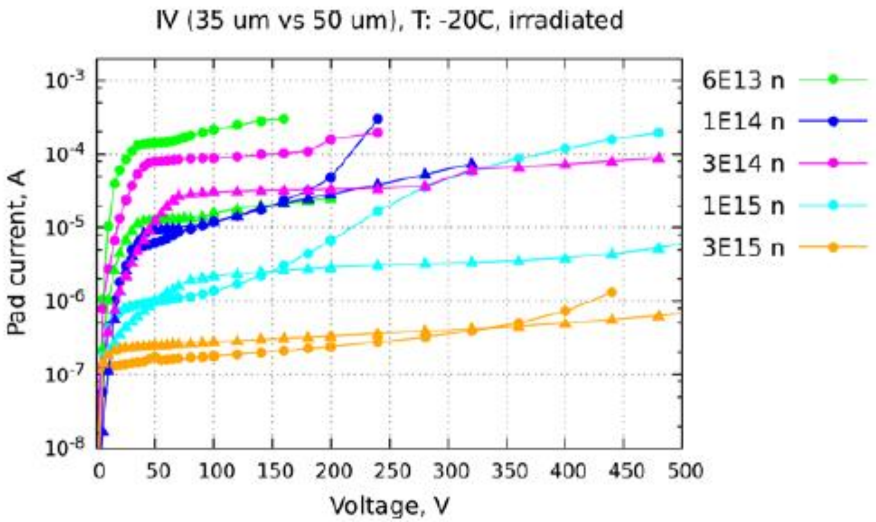
LGAD AIDAv1: IV characteristic

- High current generated at the pad periphery
- The reverse current is suppressed by irradiation
- New production to verify the origin of the problem
  - **50+300** µm thick **Si-Si**wafers
  - Increase the n+ layer to **overhang** the p+ multiplication layer, n+ implant and JTE overlap



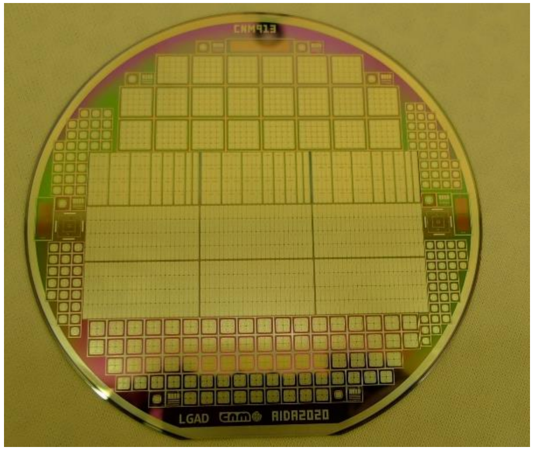

IV (35 um vs 50 um) T: 20C unirradiated

BEFORE IRRADIATION


IV (35 um vs 50 um), T: -20C, irradiated

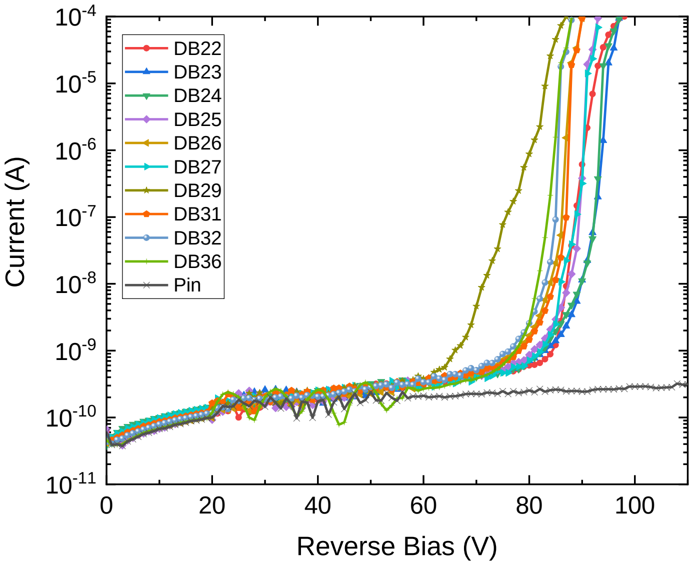
AFTER IRRADIATION

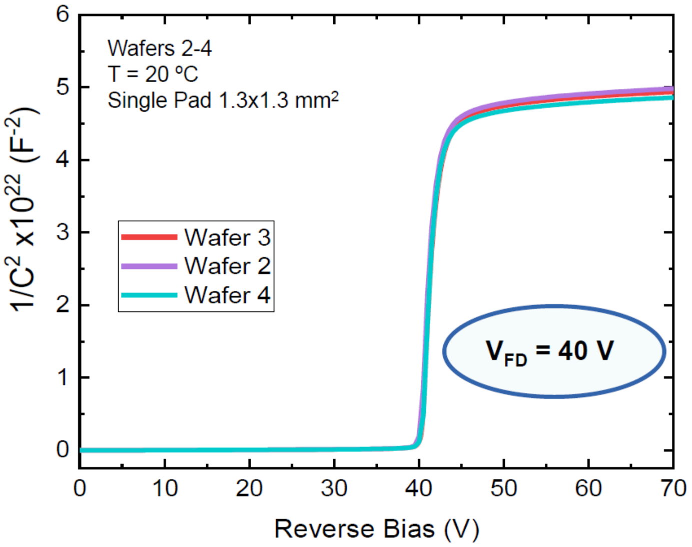
LGAD AIDAv2



Wafer	Thickness (µm)	Dose (at/cm²)	Energy (keV)
1-4	50	Medium	Low

Preliminary results show suppression of PC noise





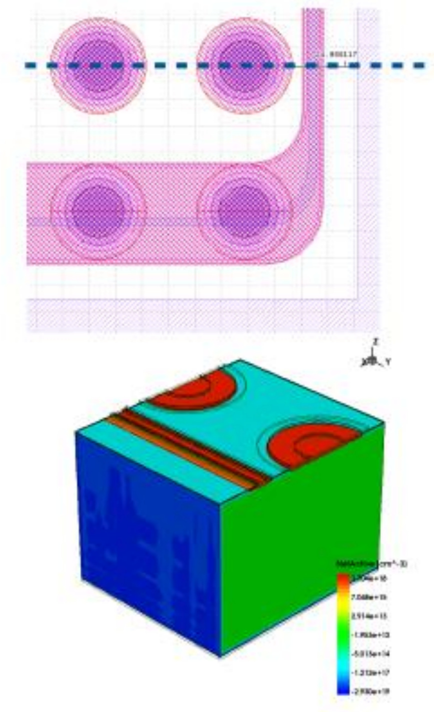
TCAD and Carrier Transport simulations

- Motivation:
  - Layout optimization.
  - benchmark against data of radiation damage models (both bulk and surface).
- For each technology dedicated simulations:
  - TCAD
  - Carrier transport codes (capacitive induced signal aka Ramo).
- Many data/simulation comparisons: dedicated test structures and test beam results.

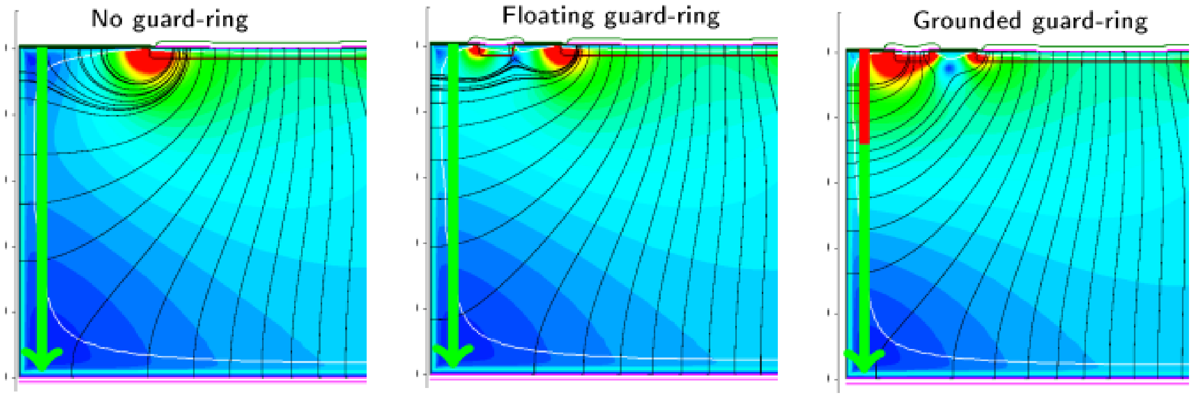
TCAD Simulation of Active-Edge planar sensors

- Focus on slim edge studies.
- Different layout and edge geometries TCAD synopsis.

Active edge sensors for CLIC



- ~ 20 µm edge, 50 µm thick
- Electric field and depleted region extend towards the edge



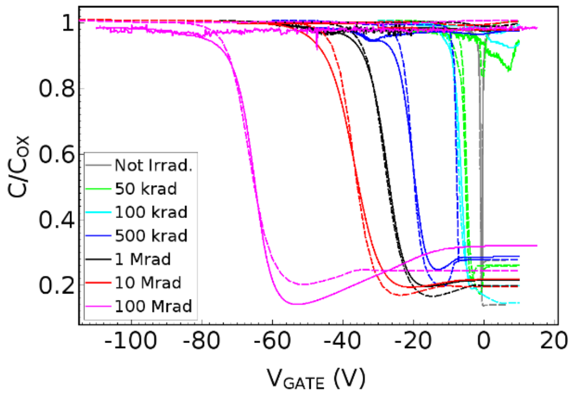
No guard-ring:
- Field lines end at the last pixel
- Expect no charge loss

Floating guard-ring:
- Most field lines end at the last pixel
- Expect only small charge loss

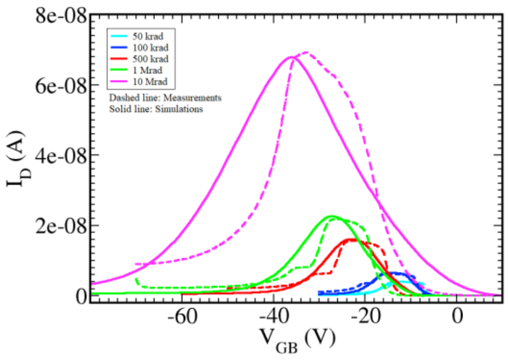
Grounded guard-ring:
- Some of the lines end at the GR
- Expect charge loss to GR

TCAD surface damage

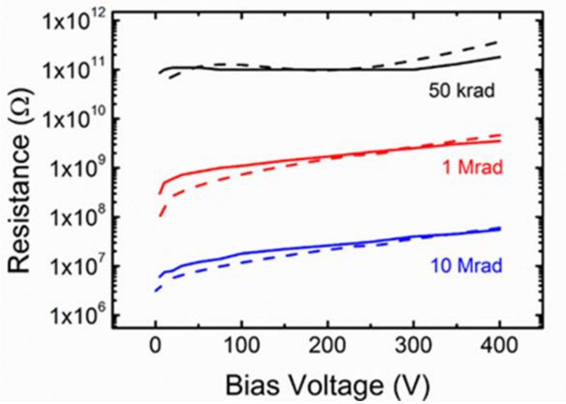
- Benchmarking of surface radiation damage model against test structures from different vendors: Infineon and HPK.



IFX MOS



HPK Gated diodes



HPK Microstrip sensors

- ✓ Extensive measurements campaign:
  - ✓ X-ray with doses 0.05-20 Mrad(SiO2).
  - ✓ Dedicated FBK, HPK and IFX p-on-n and n-on-p test structures before and after irradiation with X-rays.
- ✓ Surface radiation damage effects deeply investigated aiming at the extrapolation of the most relevant parameters:
  - ✓ cross-check of N_{EFF}, N_{IT}, N_{OX} evaluated by different methodologies from different test structures.

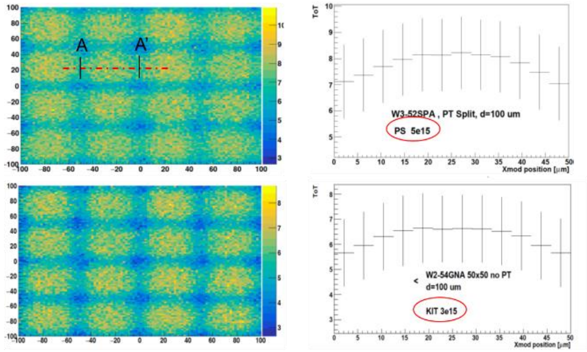
Test beam data vs simulation

- Spatial distribution of the collected charge.

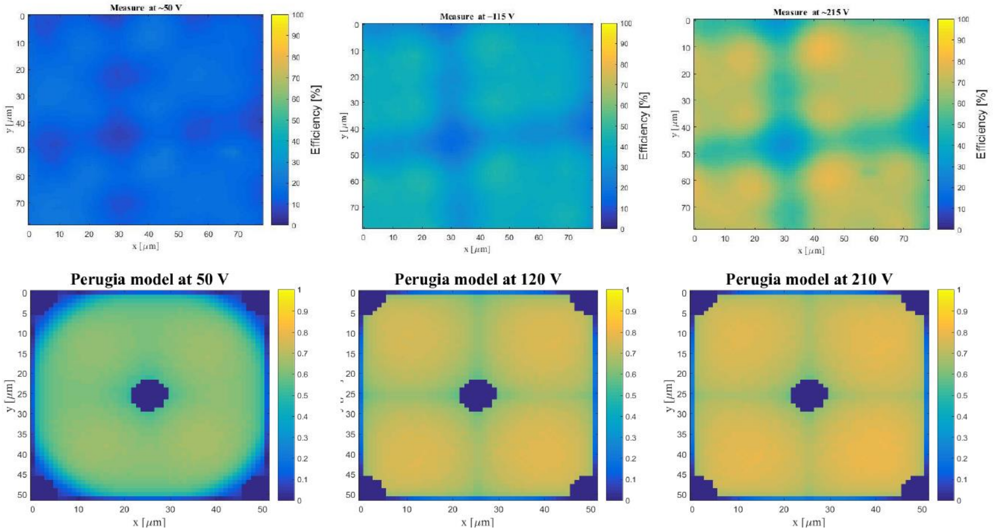
TCAD + Perugia Model → E field

E field+ Ramo-based transport code → induced signal

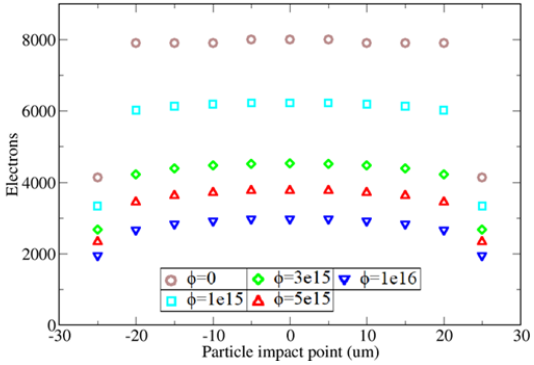
Data



SENSOR 167, 1x10^16 n_{eq} cm^{-2}



Simulation



Final Remarks

- AIDA-2020 and WP7 provided an important extra-boost to the HL-LHC pixel RD:
  - TA (Test beams and irradiations) were critical.
  - For the case of the 3D sensors the “AIDA-2020 runs” from FBK and CNM were the first (and for some time the only) source of devices to be tested.
  - RD on LGADs sensors turned out to be a right bet, not so evident five years ago at the time of the proposal
- WP7 provided to a better understanding of the different technological options for AE implementation and biasing-grid integration.
- WP7 created a unique (infrequent) coordination between RD groups from different experiments (Atlas and CMS) and different communities (simulation, manufacturing and experimental).
- All in all, it was a lot fun.

Hope to see you back soon at

AIDA innova