Studies of small-pitch CNM 3D detectors

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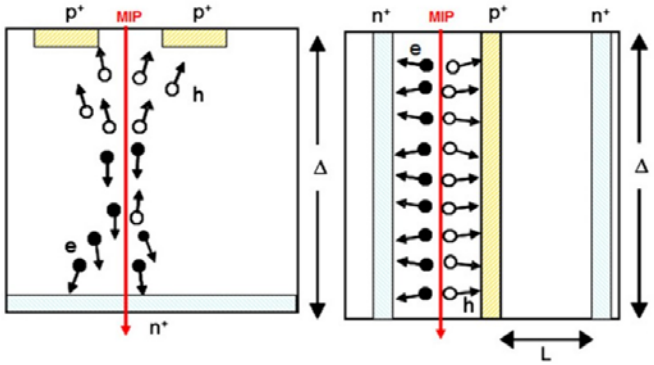
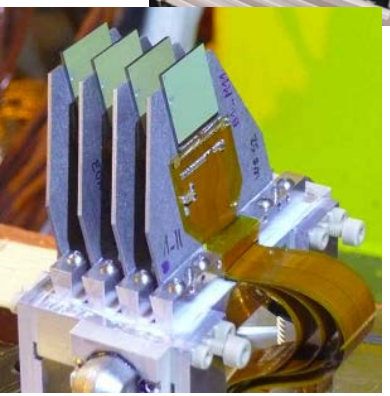
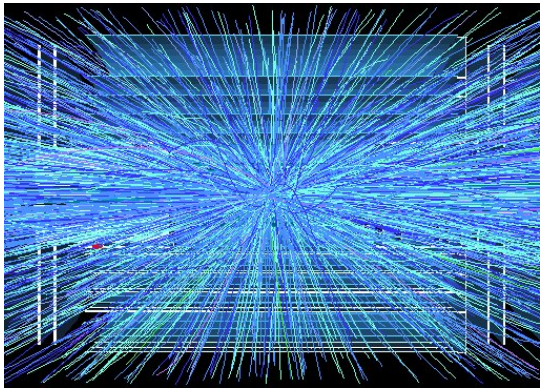
ATLAS

3D Silicon Pixel Detectors



Planar Technology 3D Technology





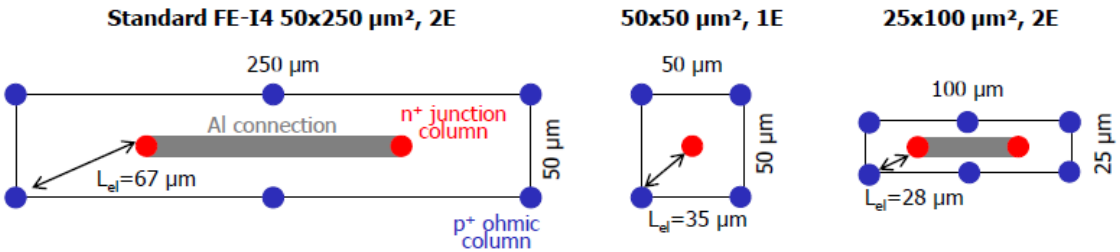
- ATLAS IBL
  - 25% 3D FEI4 detectors
  - Installed during LS1 2014/15 and running since June 2015
- ATLAS Forward Proton (AFP)
  - Successful 3D FEI4 module production Dec 2015- Feb 2016
  - Installed in Feb 2016 and running in LHC since March 2016
- CMS-TOTEM PPS
  - Sensors produced, installation planned this year
- HL-LHC pixel detectors
  - 3D promising candidate for innermost layer(s)
  - Possible installation 2024, sensor qualification for Pixel TDRs 2017

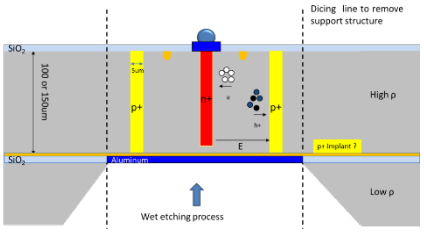
This talk

Development of HL-LHC 3D Pixel Detectors

- State of the art: IBL/AFP generation with 50x250 µm² FE-I4 pixels
  - 230 µm thick, double-sided process, ~10 µm 3D column diameter, produced at CNM and FBK
  - Slim edges of 15 µm demonstrated J. Lange et al., JINST 10 (2015) C03031, arXiv:1501.02076
  - Radiation hardness tested up to HL-LHC fluence
    - At 1e16 n_{eq}/cm²: 97% efficiency at ~180 V, 12-15 mW/cm² power consumption at -25°C
      → very low operational voltage and power consumption J. Lange et al., arXiv:1610.07480

- Development of HL-LHC 3D pixels
  - Pixel size 50x50 and 25x100 µm²
    - To cope with higher occupancies
    - Reduced electrode distance
      → more radiation hard
  - Possibly thinner
  - Different technologies available
    - Double sided (available at CNM):
      IBL/AFP-proven technology, no handling wafers needed,
      thickness limited to ≥200 µm, 3D columns ~8 µm diameter
    - Single sided (available at FBK, SINTEF, CNM):
      On handling wafer (SOI or Si-Si bonding), active thickness range 50-150 µm,
      narrow 3D columns ~5 µm possible

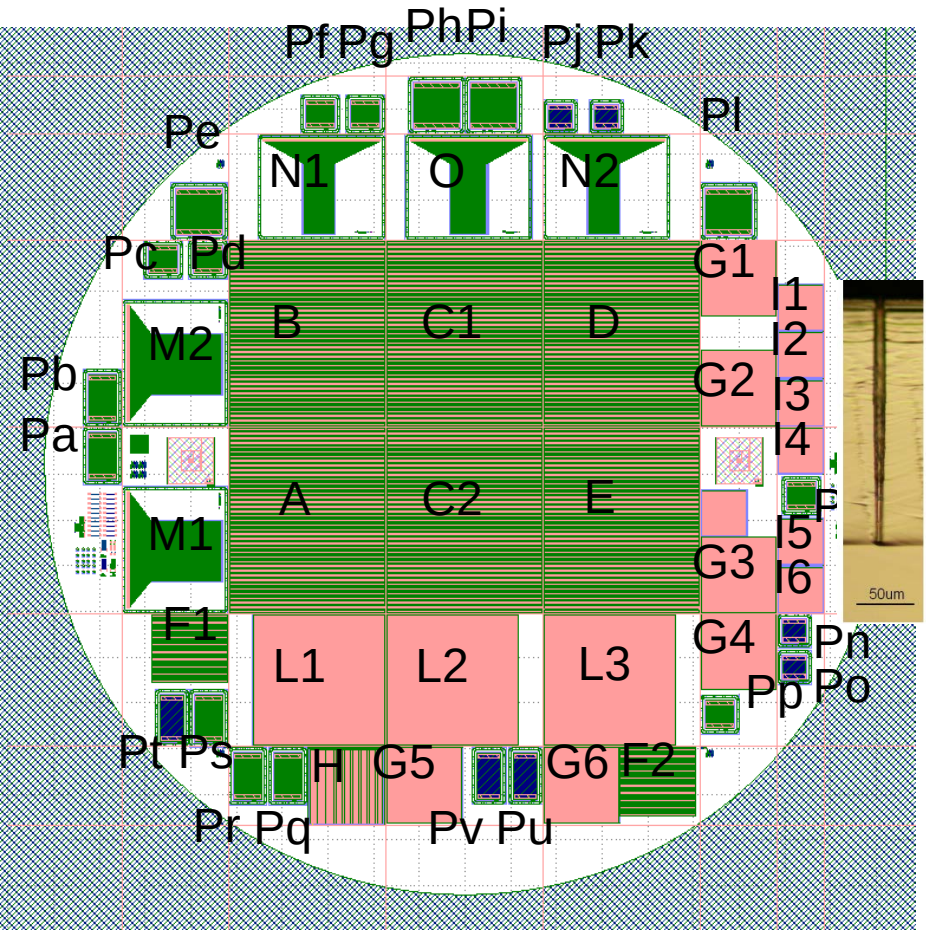




SOI
G. Pellegrini, CNM

First Small-Pixel CNM Run for HL-LHC

G. Pellegrini (more details in presentation at RD50 Workshop, Dec 2015)



D. Vazquez et al., arXiv:1610.08889

J. Lange et al., arXiv:1610.07480

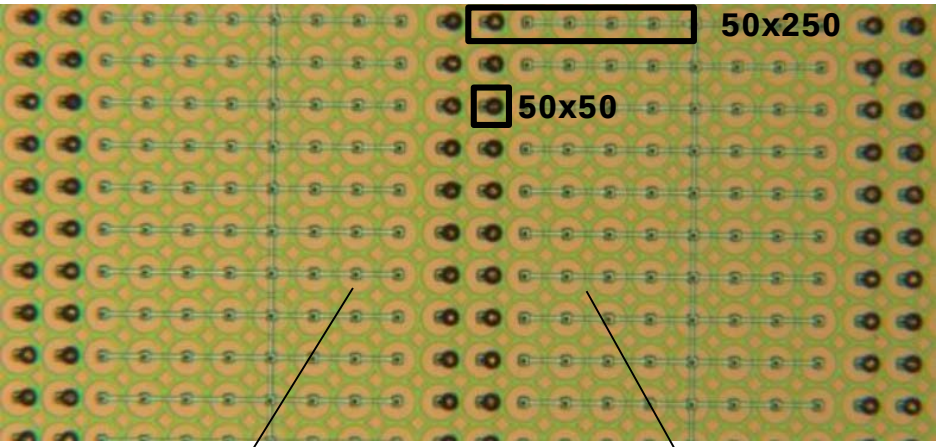
- RD50 project
- Run 7781 finished in December 2015
- 5 wafers, p-type, 230 µm double-sided, non-fully-passing-through columns (a la IBL)
- **First time small pixel size 25x100+ 50x50 µm²** (folded into FEI4 and FEI3 geometries)
  - Also strips and diodes down to 25x25 µm² 3D unit cell
- Increased aspect ratio 26:1 (column diameter 8 µm)

Number of 3D electrodes/pixel

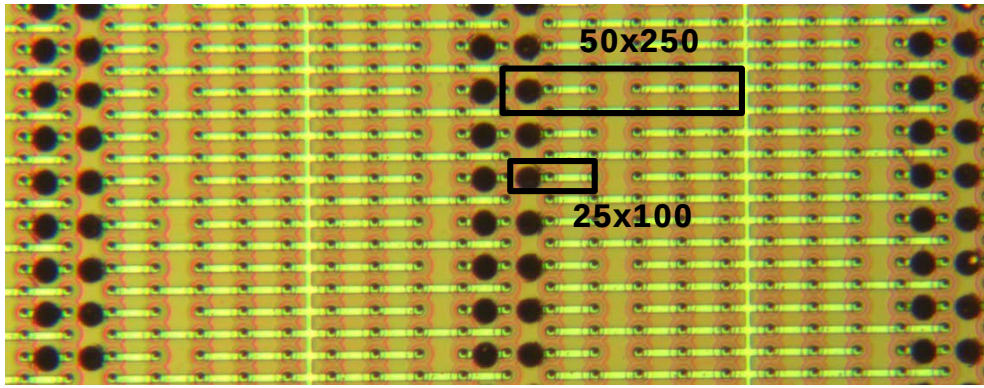
- A: 25x250 µm² 2E - standard FE-I4
- B: 25x500 µm² 5E – i.e. 5x "25x100" 1E, with 3DGR
- C: 50x50 µm² 1E with the rest connected to GND with 3DGR
- D: 25x100 µm² 2E with the rest connected to GND
- E: 50x50 µm² with the rest connected to GND without 3DGR
- F : FEI3 device: 50x50 µm² with rest to GND with 3D GR
- G: ROC4sens 50x50 µm²
- H: PSI46dig
- I: FERMILAB RD ROC 30x100 µm²
- L: Velopix 55x55 µm²
- M: Strip 50x50 µm²
- N: Strip 25x100 µm²
- O: Strip 30x100 µm²
- P: Pad diodes 25x25, 25x50, 30x50, 50x50 µm²

Small-Pixel Structures

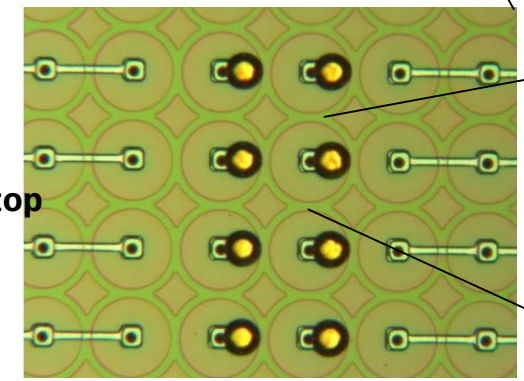
C/E: 50x50 µm² 1E
with the rest connected to GND



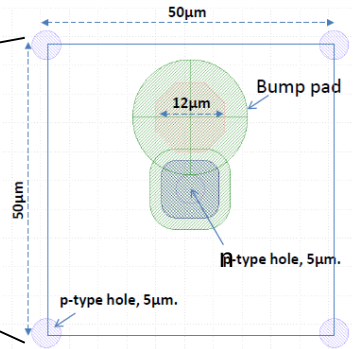
D: 25x100 µm² 2E
with the rest connected to GND



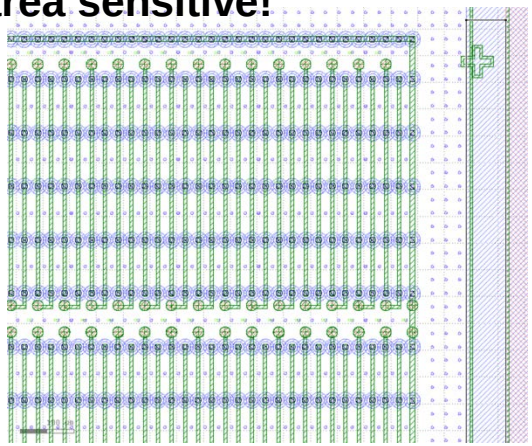
P-stop



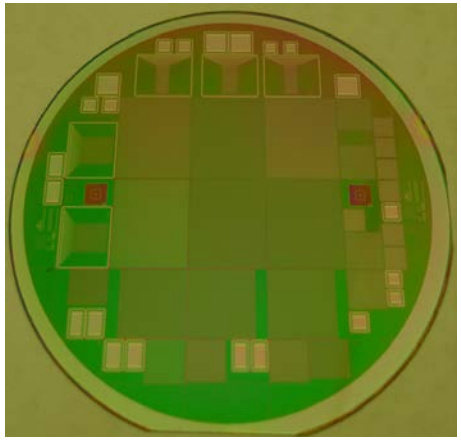
Electroless UBM



B: 25x500 µm² 5E (= 25x100 1E)
full area sensitive!

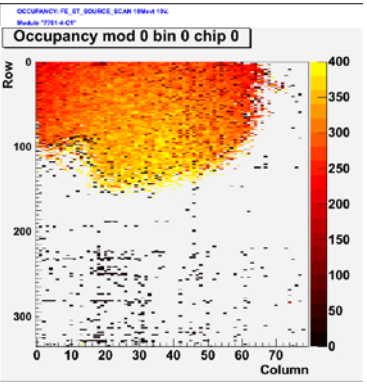


Wafer and Device Status

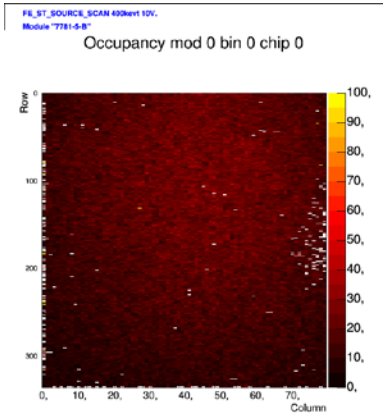


Sr90 Occupancy

Bad UBM
6 FEI4s electro-less+plate

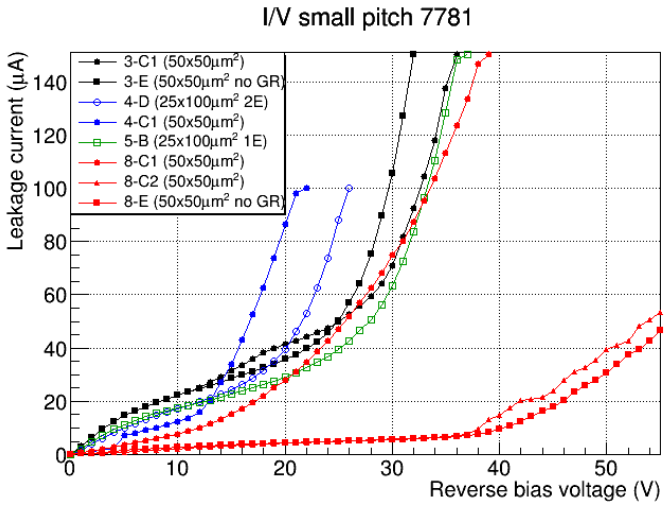


Good UBM
2 FEI4s, 1 FEI3 electro-less



- 4 wafers broke after production (handling/UBM)
  - Before special edge protection introduced at CNM
  - But recovered many pad diodes, strips and pixels
    → electro-less Au UBM at CNM on pixels
- 1 wafer survived (W8)
  → electro-plate Cu UBM at CNM on pixels
- Pixels
  - FEI4s flip-chipped, assembled and tested at IFAE
  - Many devices have disconnected bumps, 2x chip detached from sensor, but devices of 2nd UBM batch have good bump-bonding
    → UBM at CNM not yet optimized
    → But 8 FEI4s + 1FEI3 usable for testing
  - Lab characterisation, beam tests and irradiations performed and still on-going
- Strips and Pad Diodes
  - n-irradiation at JSI (0.5, 1, 1.5, 2e16 n_{eq}/cm^2)
  - IV, CV, TCT, charge collection

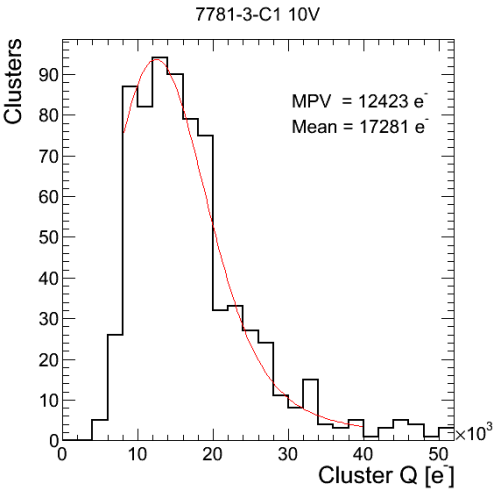
FE-I4 Pixel Characterisations

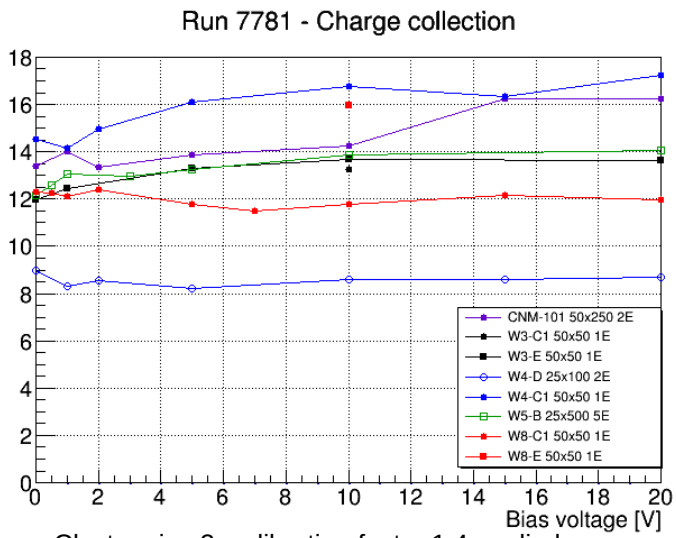


Pixel Geom.	C/el. [fF] (*)	C/pixel [fF] (*)	Noise [e]
25x100 2E	42	84	160
50x50 1E	37	37	105-140

(*) from pad diodes

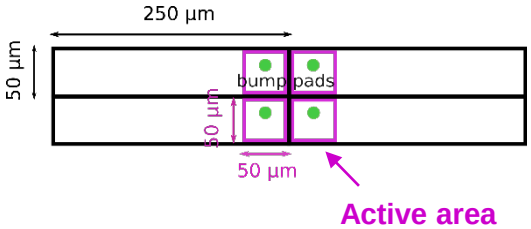
D. Vazquez et al., arXiv:1610.08889





Cluster size 2, calibration factor 1.4 applied

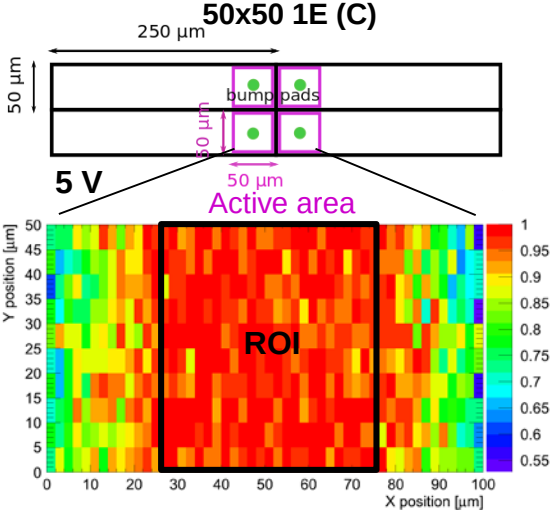
- IVs
  - V_{BD} ~ 15-40 V (produced before CNM process optimization)
- Tuning to 2ke threshold and ToT of 10BXs@20ke successful
- C <100 fF/pixel (within RD53 limit)
  - Measured on pad diodes, real pixel C might vary
- Noise similar to standard 3D FEI4s
- Sr90 source scans
  - Special care to be taken during measurement and analysis to take up to 80% insensitive area into account
  - Charge collection works, similar charge as in real FEI4s achievable



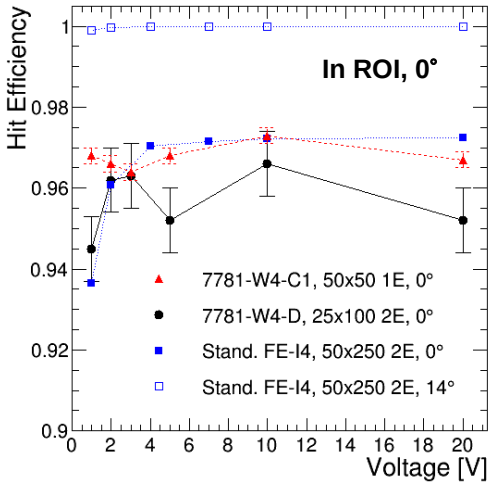
Performance in Beam Tests

In-Pixel Efficiency (FEI4 telescope, 0°)

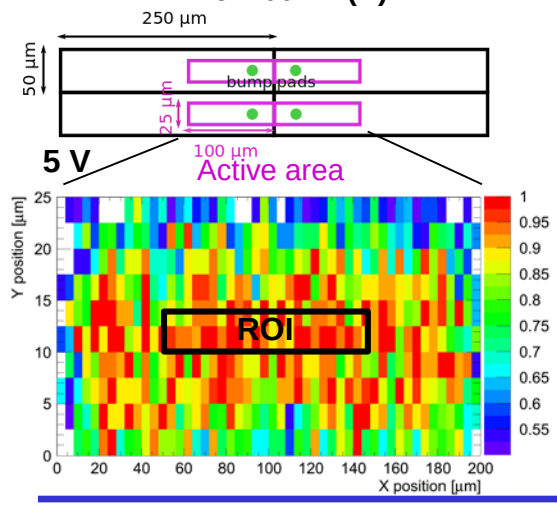
50x50 1E (C)



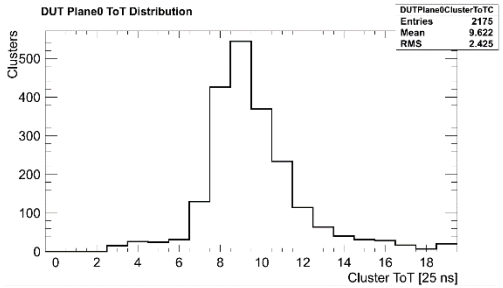
J. Lange et al., arXiv:1610.07480



25x100 2E (D)



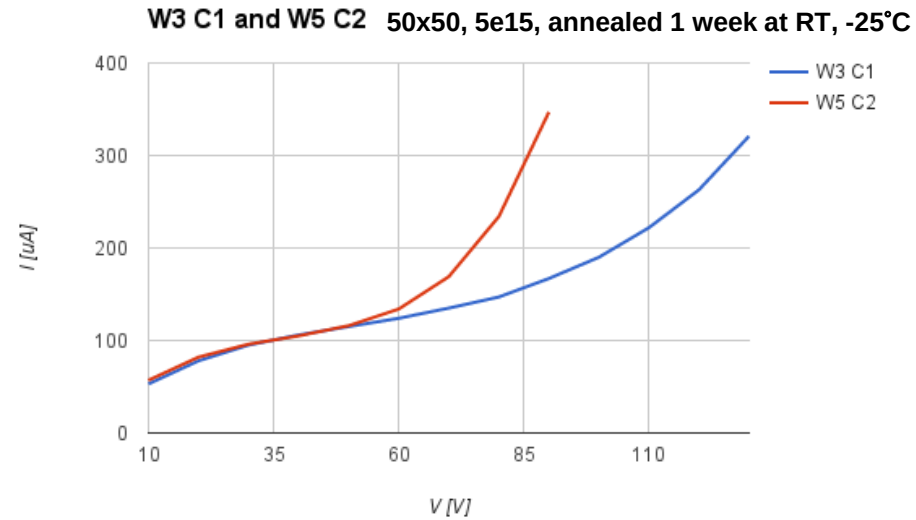
Cluster ToT

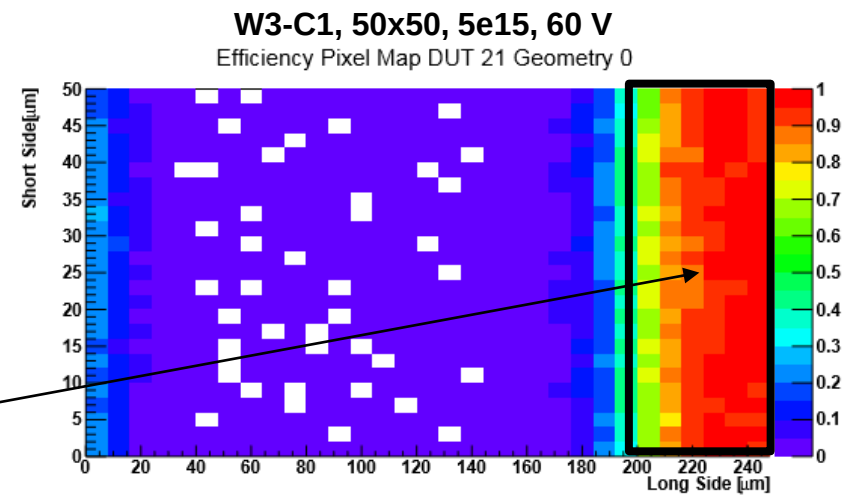


- 5 FEI4 devices measured in CERN beam tests in May+June 2016 (4 C/E 50x50, 1 D 25x100)
  - Both in AIDA-type telescope and FEI4 telescope
  - So far results with FEI4 telescope/Judith reco. (less resol. than AIDA but simpler+more robust)
- Tracks allow to select ROI within active region
  → avoid inactive area + telescope smearing
- Efficiency in ROI
  - 97% already from 1 V at 0°
  - Consistent with medium-quality-class standard FEI4 -> can be improved to 99.9% by tilting
- ToT in ROI: ~9 BXs
  - As expected for 230 µm, 10BXs@20ke tuning

Irradiated Pixel Detectors

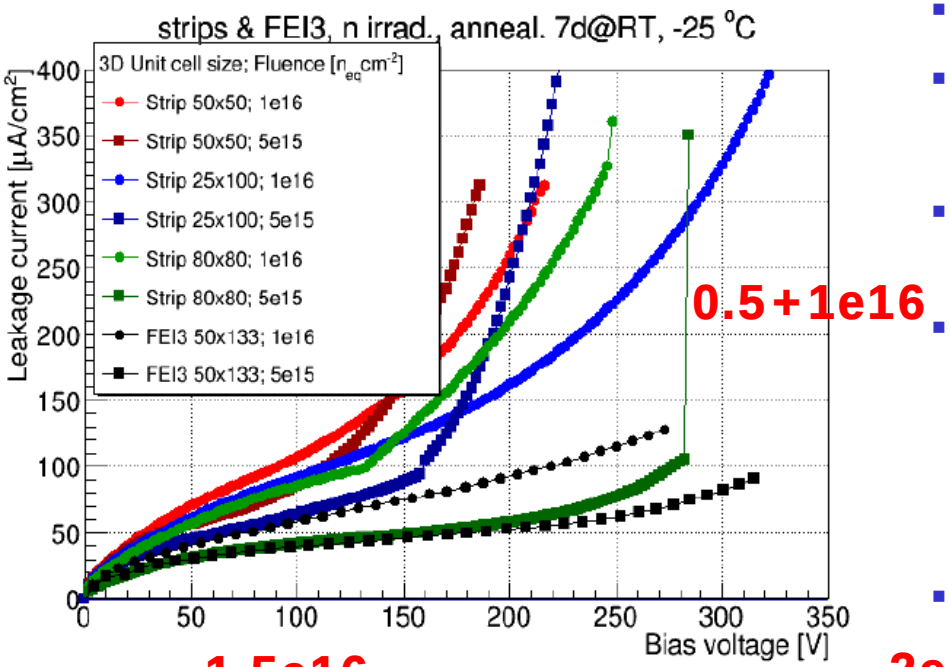
- 2 irradiation campaigns with protons
  - 3 devices at PS-IRRAD, 24 GeV p, 20x20 mm² beam, average ~1e16 n_{eq}/cm^2
    - Moderately non-uniform fluence
    - Only one device with 50x50 µm² survived (others not responsive)
      -> measured during AFP September beam test in ACONITE (EUDET-type telescope)
  - 2 devices with 50x50 µm² at KIT, 23 MeV p, 5e15 n_{eq}/cm^2 (W3-C1, W5-C2)
    - Uniform fluence at IBL benchmark point → ideal for comparison to IBL-generation 3D geometries
    - IV: W3-C1 operable up to 130 V, W5-C2 breaks earlier
    - Measured in October ITk Pixel beam test in ACONITE
    - Analysis on-going





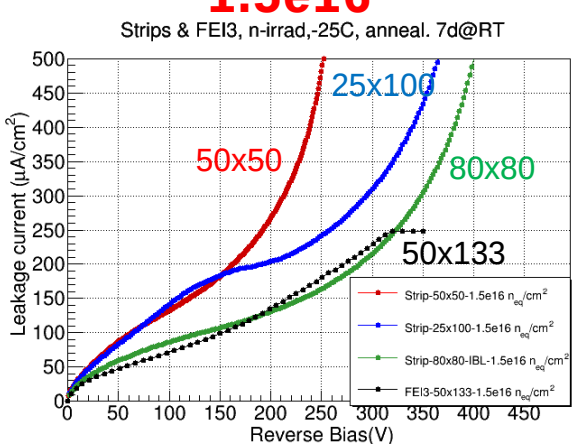
50x50 sensitive region

IV after Irradiation for Different 3D Geometries

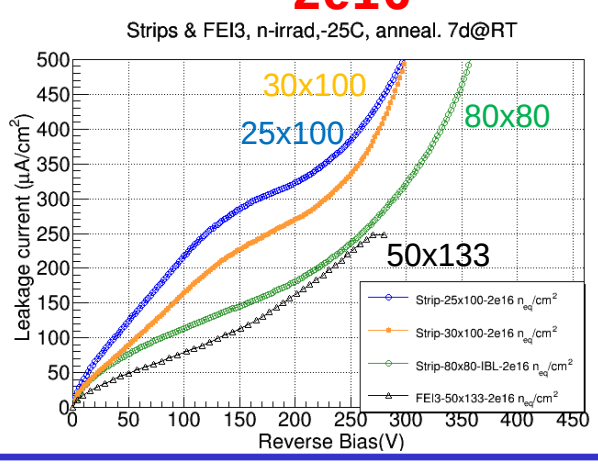


- Strip irradiation at Ljubljana
- Results up to 1e16 n_{eq}/cm^2 showed **higher I_{leak} and lower V_{BD} for smaller 3D cell sizes**
  D. Vazquez et al., arXiv:1610.08889
- New results at 1.5+2e16 n_{eq}/cm^2 confirm trend that devices from new small-pitch run have higher I_{leak}
- Still under investigation
  - Artifact of this run?
    (before CNM process optimisation)
  - Or real trend for smaller 3D cell sizes due to higher el. field and multiplication?
- Still much lower than RD53 limit of 10 nA/pixel

1.5e16

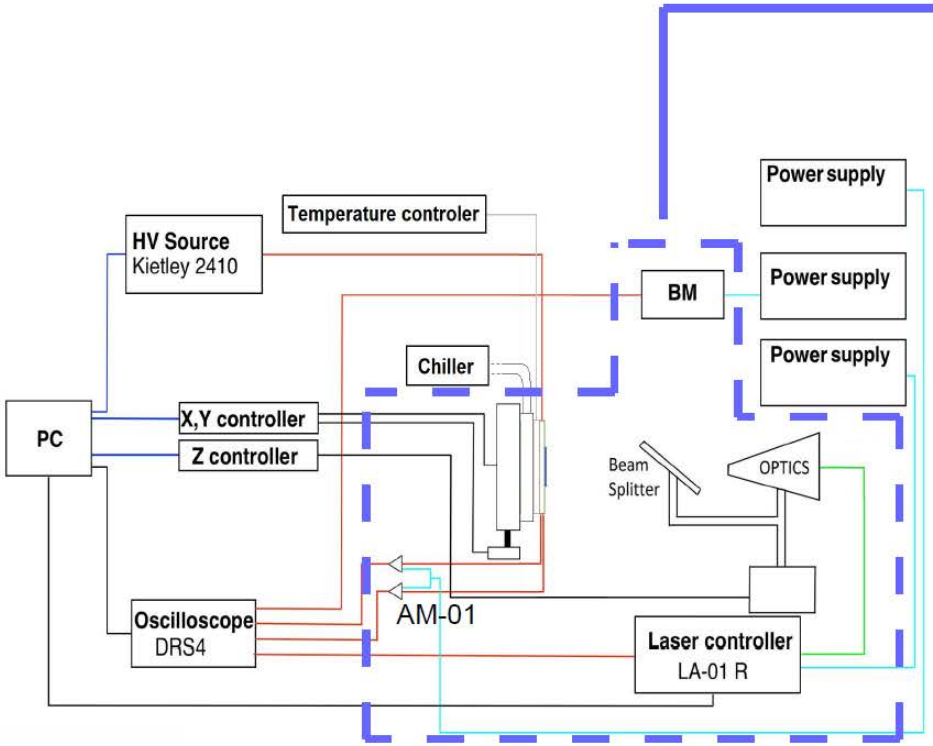


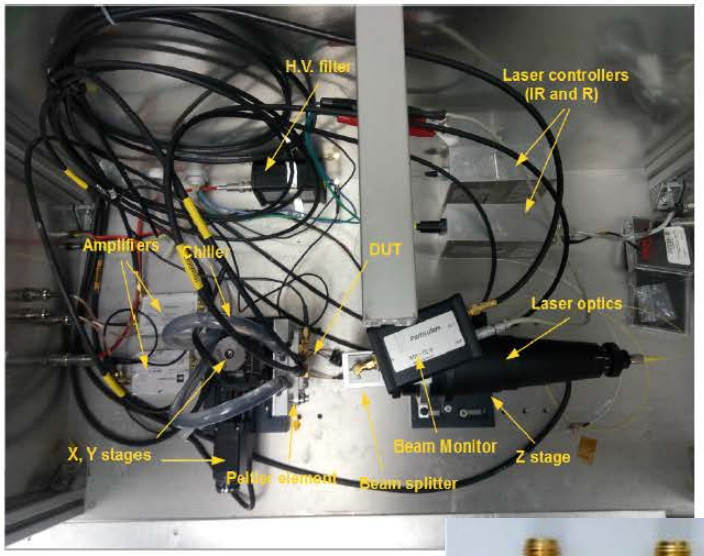
2e16



- **V_{op} will be lower for smaller 3D cell sizes due to better radiation hardness**
  → compensating effect
  → V_{op} to be determined in beam tests (on-going)

TCT on Strip

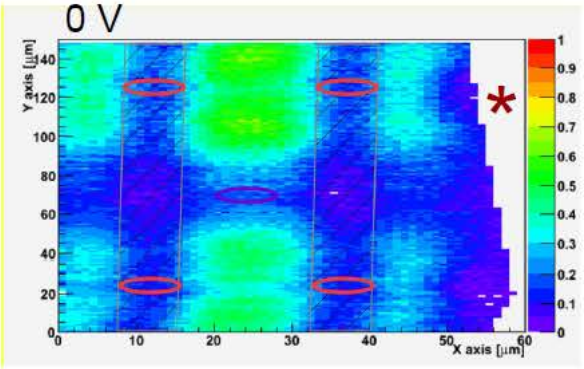


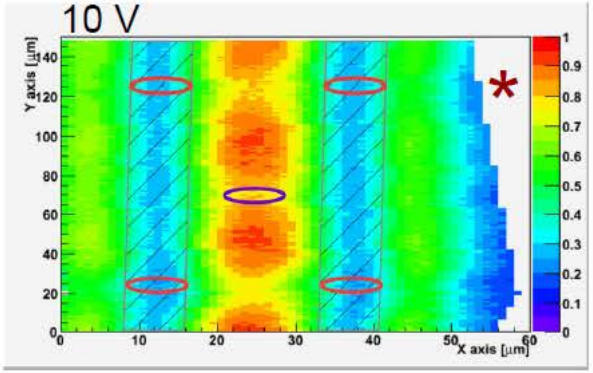


- TCT setup at IFAE Barcelona: scanning TCT from Particulars
- DRS4 readout
- Peltier cooling to -10°C
- TCT PCB developed by DESY/Hamburg
- Surface scan with 1060 nm IR laser
- Normalised to beam monitor

Unirradiated Strips: 2D Charge Maps

25x100 μm²:

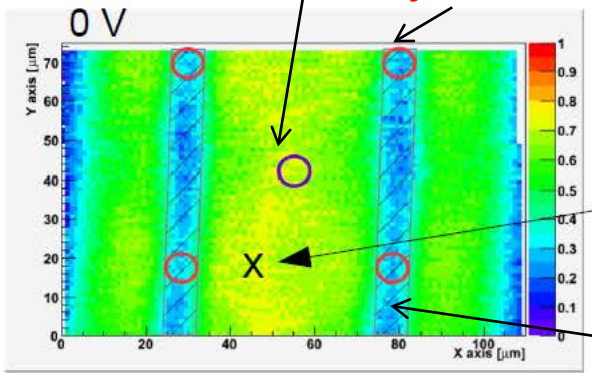


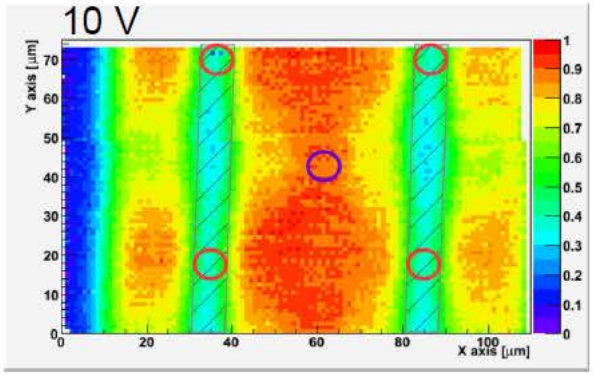


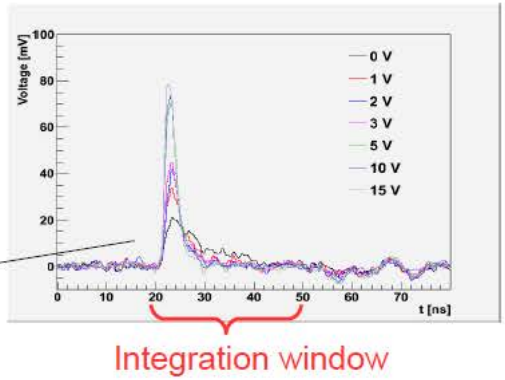
50x50 μm² :

p+ ohmic column

n+ junction column







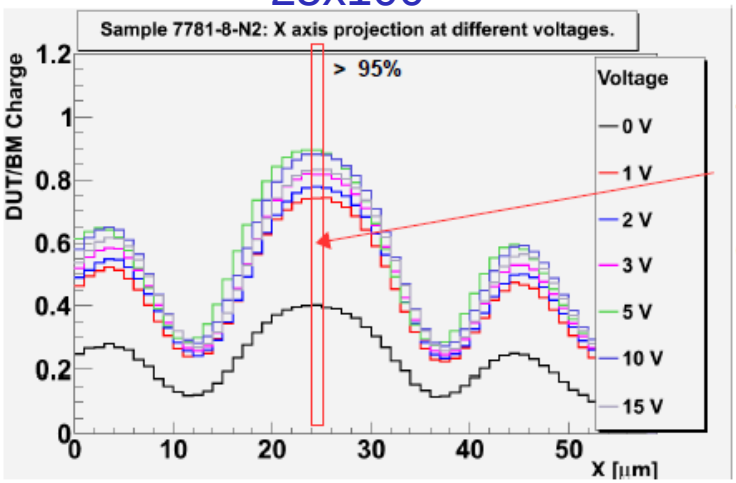
Aluminium strip (2 read out)

* White bin region due to offline correction of artificial bending caused by stage controller issue

- 2D maps normalized at different scales! → maximum charge in each geometry (0.126 in 25x100 μm² and 0.196 in 50x50 μm²)
- Even at 0 V, charge collected near the n^+ columns
- As the voltage is increased, the depletion region (charge collection) around the n^+ columns increases

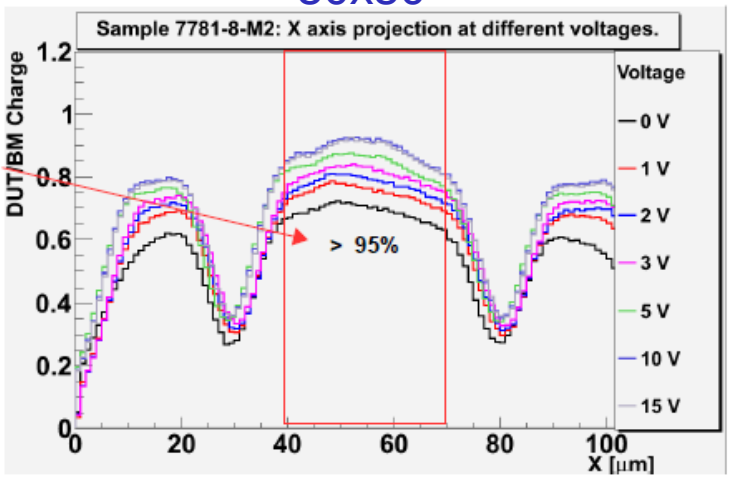
Unirradiated Strips: 1D Charge Profile

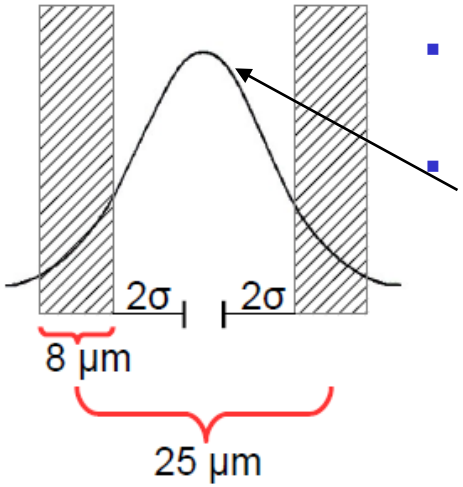
25x100



Theoretical laser intensity plateau regions assuming σ = 4 µm

50x50





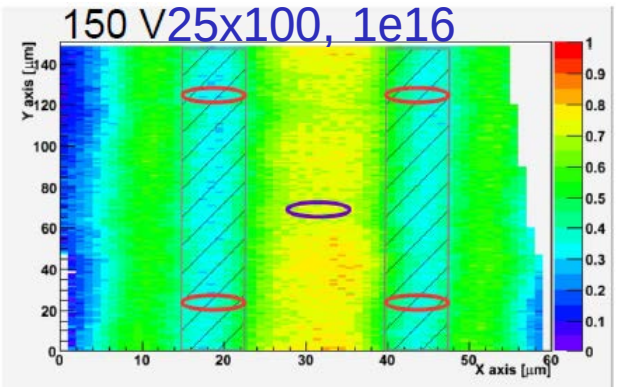
- Plateau for 50x50
  -> easy to take average charge
- Problem for 25x100: Sensitive area in same order as laser σ~4 µm
  - If well focused to σ~4 µm, only 1 µm between Al that contains 95% of laser beam
    -> take 1 µm as ROI, need to normalize different geometries separately
  - Small focus variations lead to large charge fluctuations
    -> very difficult to compare different samples and calculate CCE

Irradiated Strips: 2D Charge Maps

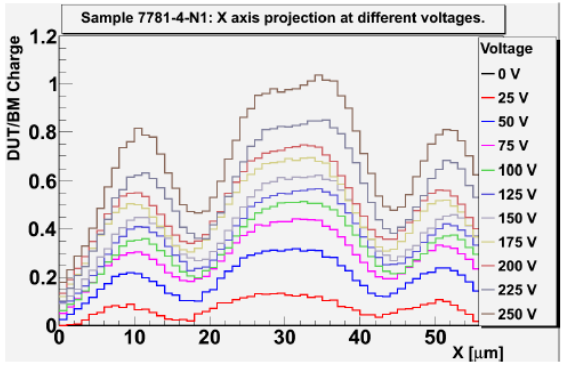
25x100

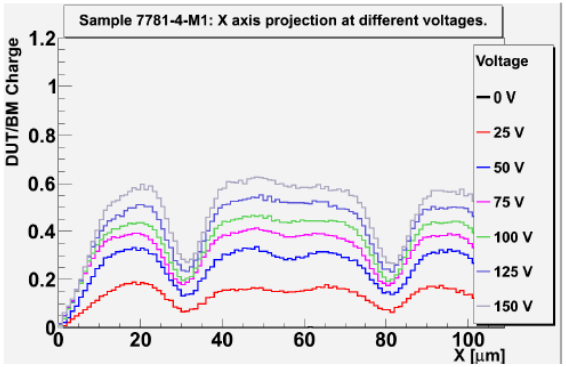
50x50

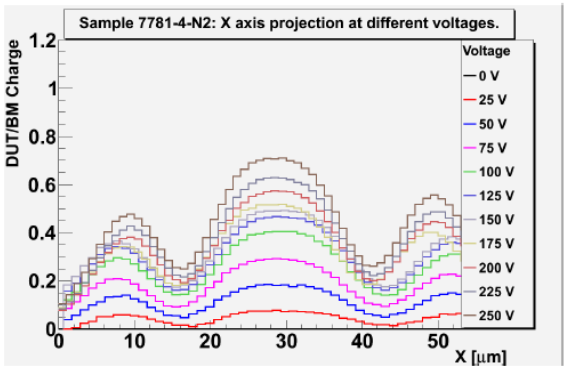
5e15

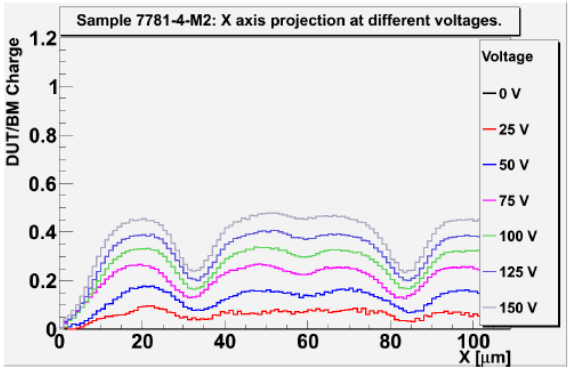


1e16



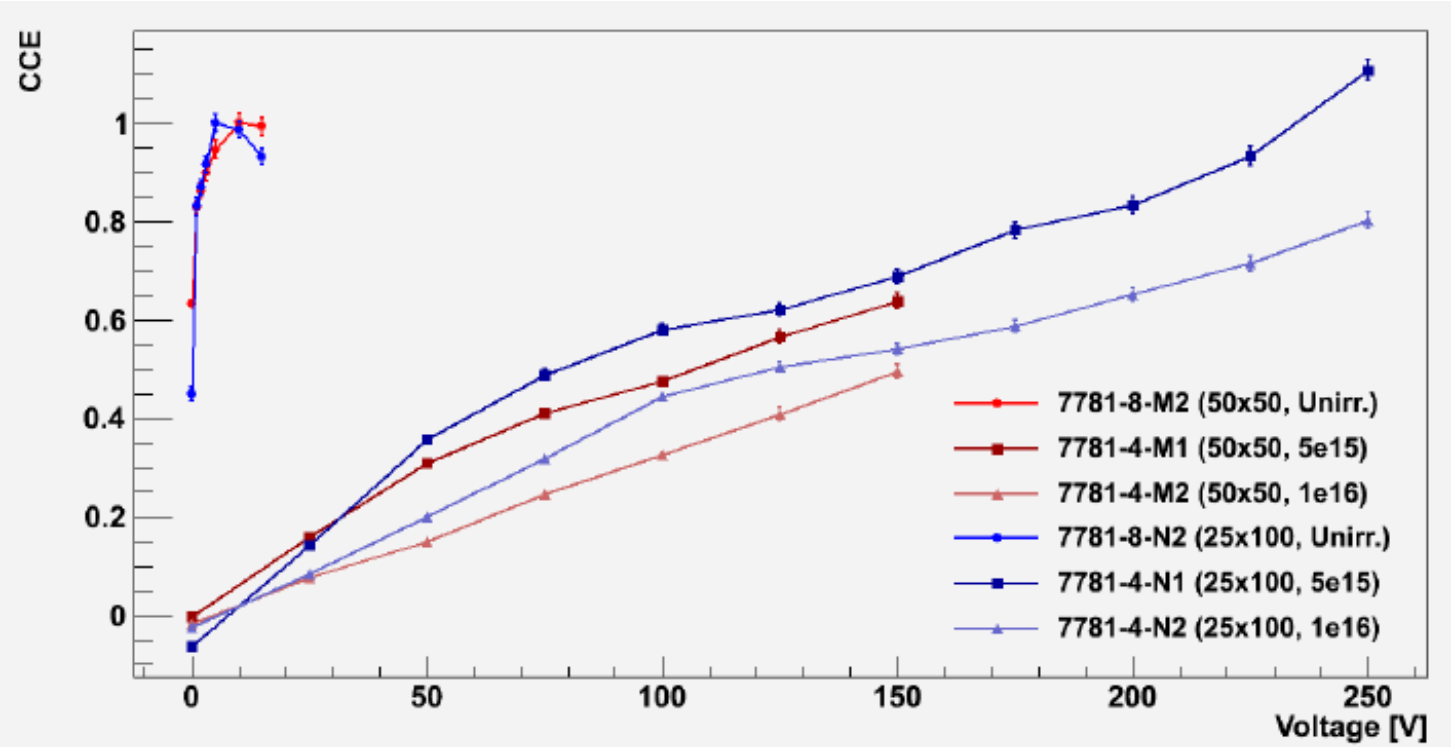






- Relatively uniform charge collection at 150 V
- Charge strongly increasing with V
- Plateau in irradiated 25x100 µm² seems wider than before irradiation
  -> laser better focused?
  -> large uncertainties when normalizing to unirradiated sensor for CCE

Irradiated Strips: CCE vs. V



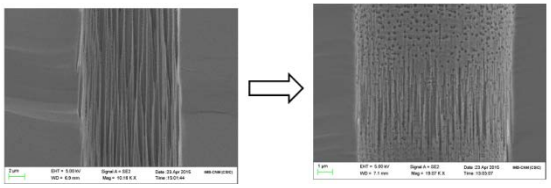
- High CCE at relatively low V
  - 50x50: up to 65% measured for 5e15 and 50% for 1e16
  - 25x100 slightly more at the same voltage – Would expect less CCE if electrode distance is larger! Possibly due to better focused laser in irradiated 25x100 μm² measurements than in the unirradiated one?
  - Also change of absorption after irradiation still under investigation

-> needs cross check with beta source (ALIBAVA measurements planned)

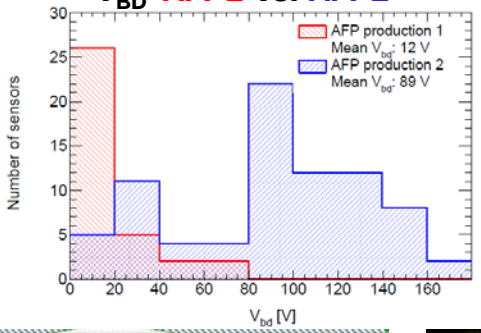
- Effects of charge multiplication at high V? *Observed previously in 80x80 strips by M. Koehler et al., NIMA 659 (2011) 272*

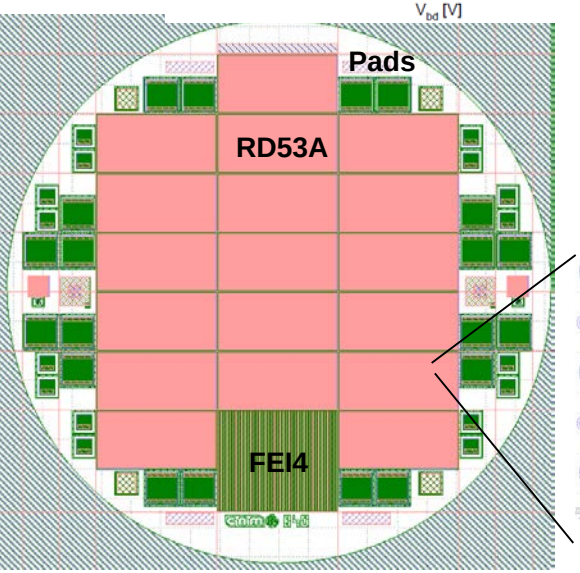
Up-coming 3D Runs at CNM

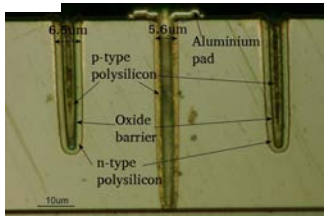
IBL / AFP1 / 7781 **AFP2 / CT-PPS**

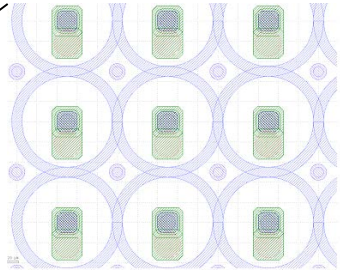


V_{BD} AFP1 vs. AFP2









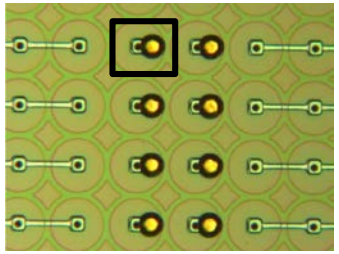
- CNM largely improved 3D process
  - Better DRIE process reduced side wall defects, also edge protection → **huge yield improvement** in AFP2 run (85%)

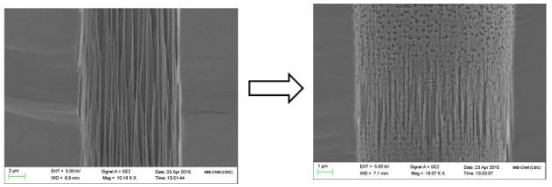
    S. Grinstein et al., arXiv:1611.01005
- New run as copy of 7781 with improved process
  - Production on-going → expected for February 2017
- Thin 3D runs with 7781 mask (100-150 µm on SOI)
  - Production on-going → expected for February 2017
- Runs with RD53A pixel devices
  - Single-sided 72, 100+150 µm: expected for mid 2017
  - Double-sided 200 µm planned later (AIDA2020)
  - Devices
    - 14 RD53A 50x50 µm² 1E
    - 4 RD53A 25x100 µm² (2x 1E, 2x 2E)
    - 1 FEI4 50x50 µm² 1E (equivalent to 7781 C)
    - Pad diodes of 50x50 µm² and 25x100 µm²
- Investigating collaboration with Glasgow
  - Could transfer part of DRIE processing to Glasgow to increase production capabilities for 3m² scenario

Conclusions and Outlook

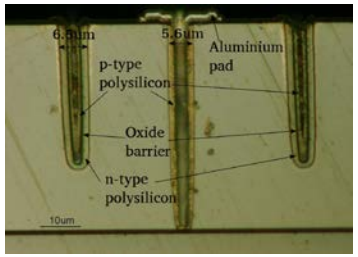
- First new-generation 3D production with small HL-LHC pixel size
  - Characterisations and beam tests of 50x50 and 25x100 µm² FEI4s performed
    - Good performance before irradiation as expected
    - 97% efficiency at 1 V and 0°
  - Beam tests performed with irradiated small-pixel 3Ds
    - Analysis on-going
  - Measurements on strips irradiated with n up to 2e16 n_{eq}/cm^2
    - Higher I_{leak} than for IBL-type still under investigation, but will need less V_{op}
    - High CCE measured in TCT: 50% at 150 V for 1e16 n_{eq}/cm^2
      - But especially 25x100 µm² needs cross check with source

50x50 µm²





- Process optimisations performed at CNM
  - Highly improved yield (demonstrated by AFP2 production)



- Single-sided thin 3D and RD53-chip geometry under way at CNM
  - 72, 100 + 150 µm SOI

5th Beam Telescopes & Test Beams Workshop

In 2010 RD50 Workshop venue!!
(Raval, downtown)
Tour and dinner in Gaudi house!

24th - 27th January 2017, Barcelona

https://indico.desy.de//event/bttb5

Topics:
Beam lines & infrastructures
Beam telescopes & device integration
Data analysis, tracking, alignment
Simulations & software packages

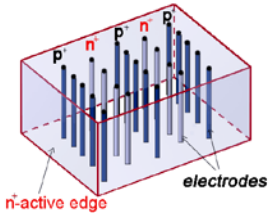
Abstract submission deadline: **23-12-2016**
Registration deadline: **23-12-2016**

Organising Committee:
Jan Dreyling-Eschweiler (DESY)
Hendrik Jansen (DESY)
Joern Lange (IFAE)
Iván López (IFAE)
Simon Spannagel (CERN)
Stefano Terzo (IFAE)

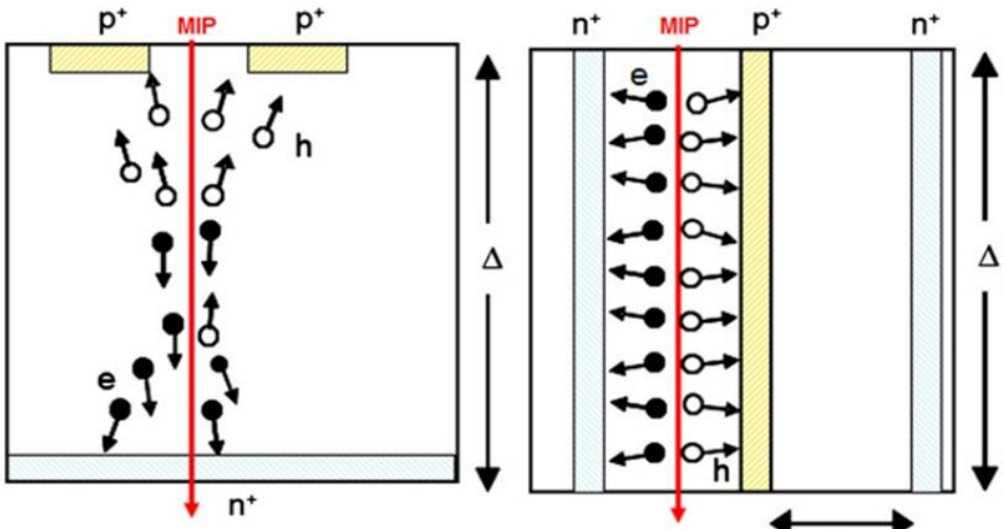
IFAE Institut de Física d'Altes Energies
DESY

BACKUP

3D Detector Principle



Planar Technology 3D Technology



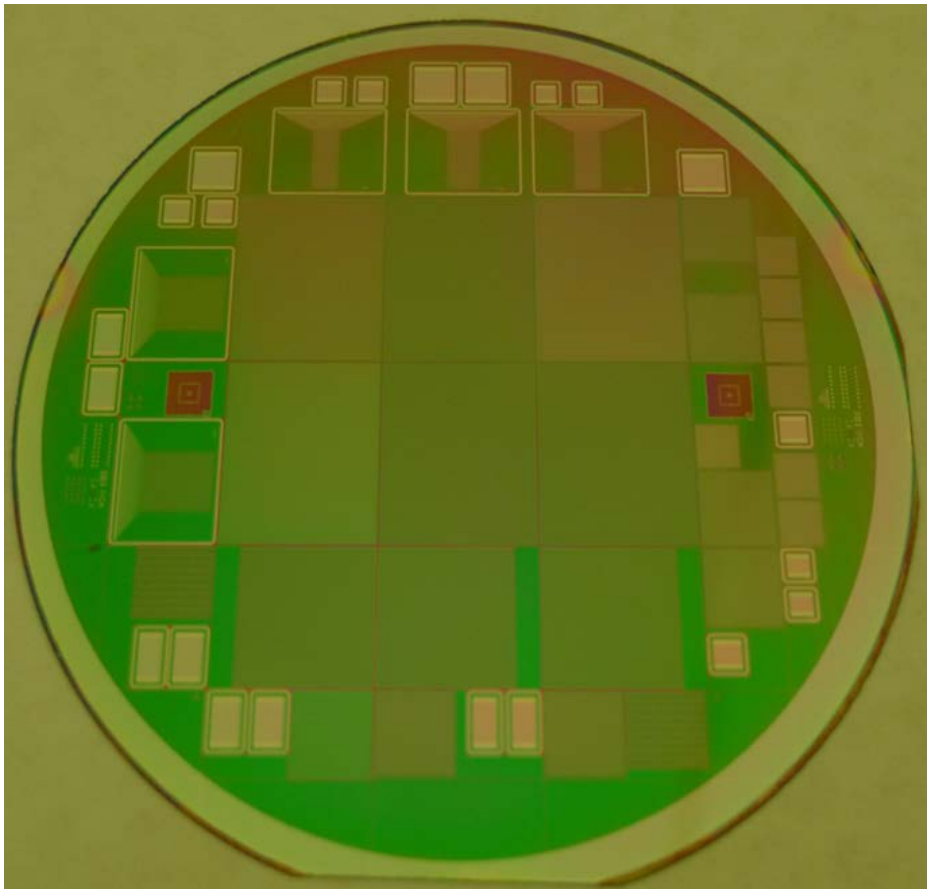
C. Da Via et al., NIM A 694 (2012) 321

Radiation-hard and active/slim-edge technology

- **Advantages**
  - Electrode distance decoupled from sensitive detector thickness
    → lower $V_{depletion}$
    → less power dissipation, cooling
    → smaller drift distance
    → faster charge collection
    → less trapping
  - Active or slim edges are natural feature of 3D technology
- **Challenges**
  - Complex production process
    → long production time
    → lower yields
    → higher costs
  - Higher capacitance
    → higher noise
  - Non-uniform response from 3D columns and low-field regions
    → small efficiency loss at 0°

Wafer and Columns

G. Pellegrini, D. Quirion



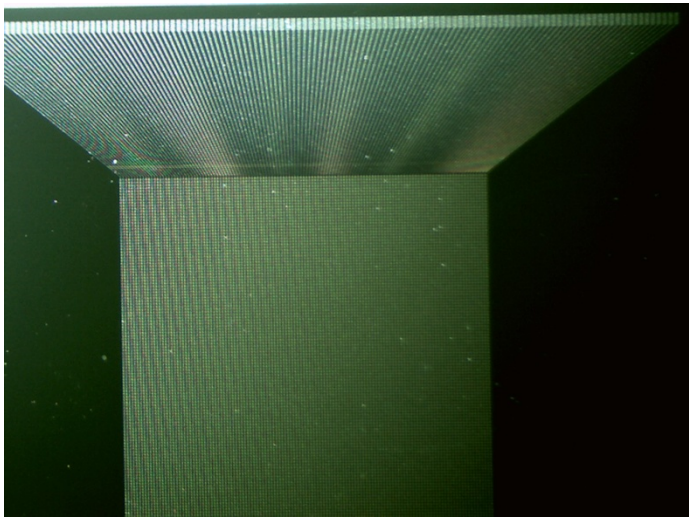
IBL
3D Diameter
Nominal 10 µm
Maximum 13 µm

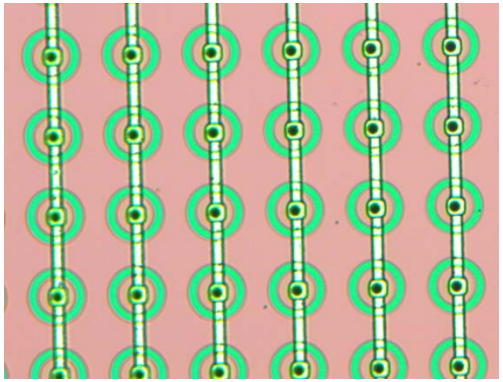
7781
3D Diameter
Nominal 8 µm
Maximum 10 µm

→ Increased aspect ratio 26:1 (nom.)

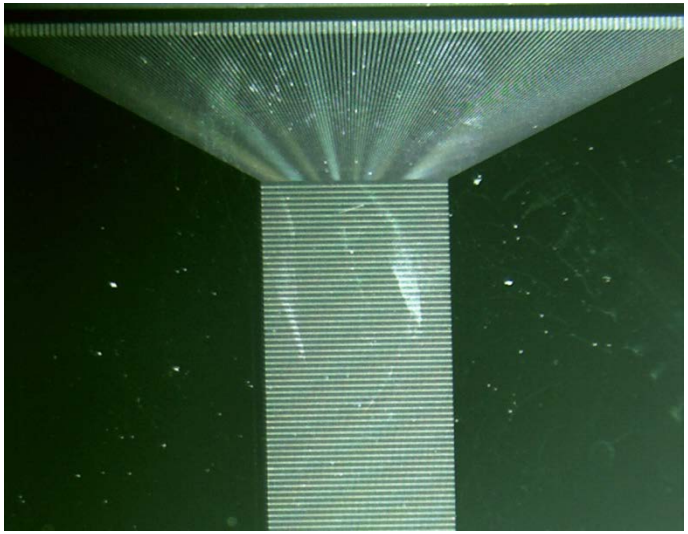
Strips

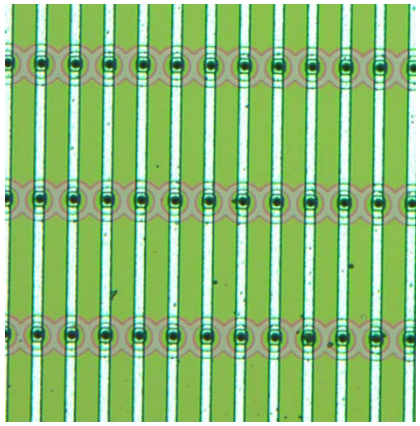
50x50 µm² 3D unit cell
128 strips, 150 3D columns each



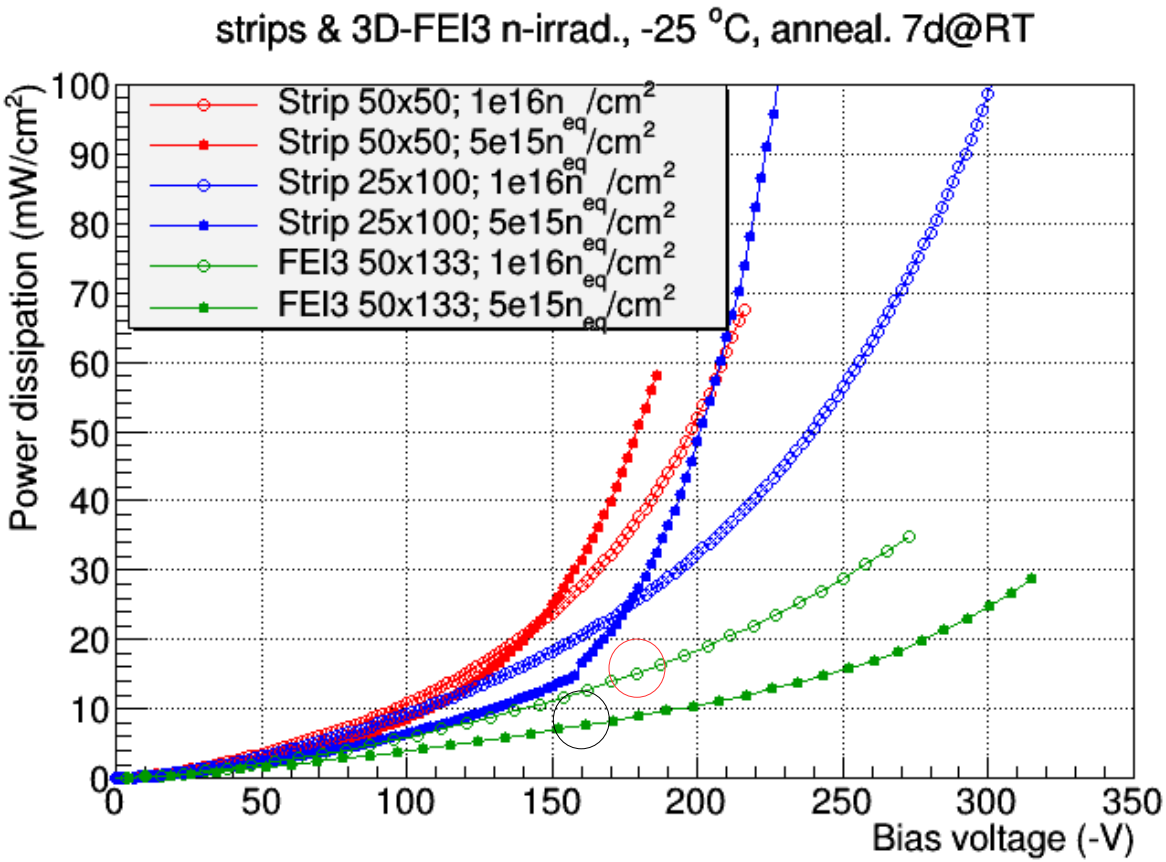


25x100 µm² 3D unit cell
128 strips, 75 3D columns each



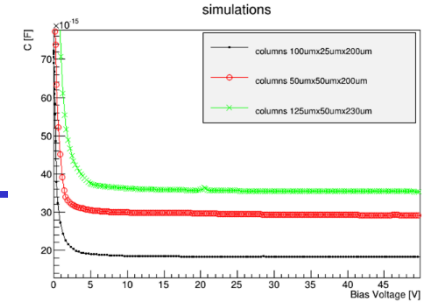


Power after Irradiation for Different 3D Geometries

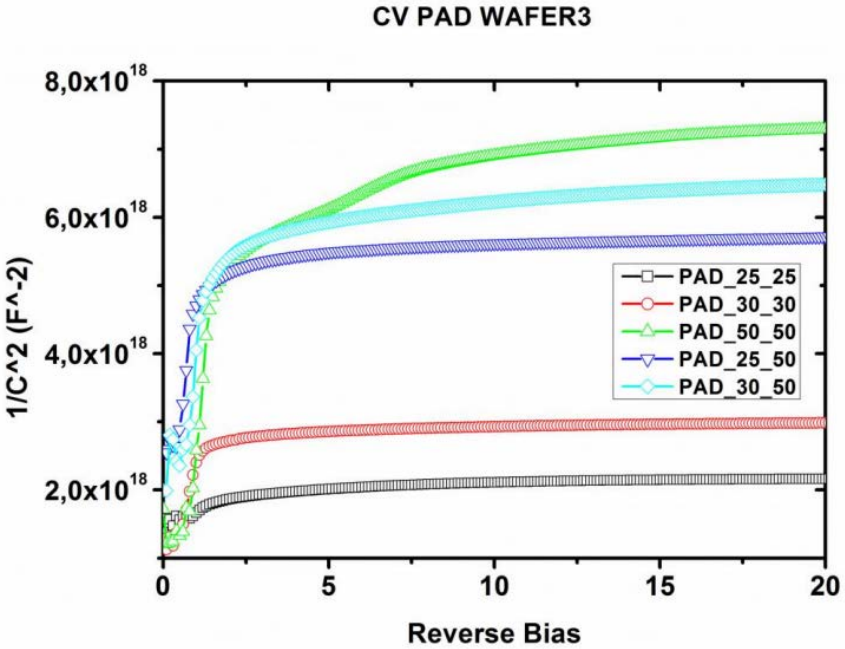


- For same V, P is higher for smaller 3D cell sizes
- **But V_{op} will be lower for smaller 3D cell sizes**
  → compensating effect for power
  → V_{op} to be determined in next beam test (next week!)
  - For example:
    for the same power dissipation as for FEI3 at 1e16 n_{eq}/cm^2 and 180 V (15 mW/cm²), the 50x50 structures need to be operated at 120 V

Capacitance

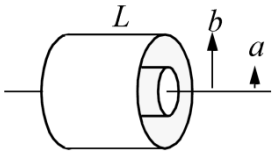


Measurements by M. Carulla



Unit Cell	Electrode Distance [µm]	C/column [fF]
25x25	18	69
30x30	21	58
25x50	28	42
30x50	29	39
50x50	35	37

- On diodes at wafer level
- Different diode geometries
  - All different 3D unit cell (25x25 up to 50x50 µm²)
  - All 100x100 3D columns each
- Capacitance increases with smaller electrode distance
  - Trend similar to simple capacitance of a cylinder (but 3D capacitance has also other contributions):



$$C = \frac{2\pi\varepsilon_0 L}{\ln\left(\frac{b}{a}\right)}$$

- Pixel capacitance (without bump)
  - 50x50 1E: 37 fF
  - 25x100 2E: 84 fF
  - 25x100 1E: << 42 fF (to be measured)

→ Within RD53 limit of 100 fF/pixel

Compilation of Current and Power Dissipation for IBL-Generation

Fluence [n_{eq}/cm^2]	V_{op} [V]	Irradiation	Sample	Thick-ness [µm]	Electrode Distance [µm]	Column Diam. [µm]	I/area for 230 µm [µA/cm²]	P/area for 230 µm [mW/cm²]
5e15	160	n (Ljubljana)	CNM FEI3 Pixel [1]	230	71	13	46	7.4
		23 MeV p (KIT)	CNM34 FEI4 Pixel [2]	230	67	13	34	5.4
		23 MeV p (KIT)	CNM97 FEI4 Pixel [2]	230	67	13	39	6.3
		23 MeV p (KIT)	FBK11/87 FEI4 Pixel [2]	230	67	11	37	5.9
		n (Ljubljana)	CNM81 FEI4 Pixel [2]	230	67	13	46	7.3
		23 MeV p (KIT)	CNM strip 1 [3]	285	57	13	41	6.5
		23 MeV p (KIT)	CNM strip 2 [4]	285	57	13	44	7.0
		23 MeV p (KIT)	FBK strip [5]	230	57	11	38	6.1
		n (Ljubljana)	CNM diode [6]	50	57	6	48	7.7
1e16	180	n (Ljubljana)	CNM FEI3 Pixel [1]	230	71	13	83	14.9
		23 MeV p (KIT)	CNM strip 1 [3]	285	57	13	86	15.5
2e16	200	n (Ljubljana)	CNM FEI3 Pixel [1]	230	71	13	160	32.0
		23 MeV p (KIT)	CNM strip 2 [4]	285	57	13	98	19.6
		23 MeV p (KIT)	FBK strip [5]	230	57	11	158	31.6

- Comparison between different 3D devices and irradiations (p, n)
- All values scaled to -25°C, 7d@RT annealing and 230 µm thickness
- Good agreement: max. 39% deviation per fluence (usually better)
- Thickness scaling works (between 50 and 285 µm)
- Independent of
  - Column diameter (beetween 6 and 13 µm)
  - Electrode distance (between 57 and 71 µm)

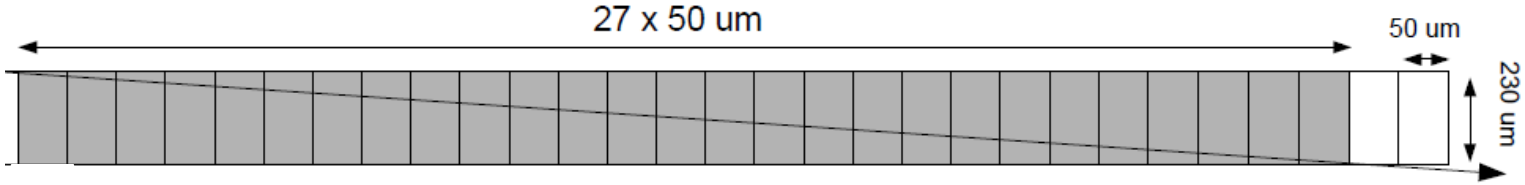
[1] Measured by IFAE 2015 at -25˚C, 7d@RT annealing (this talk)
[2] ATLAS IBL Coll., JINST 7 (2012) P11010, remeasured by IFAE 2015 at -25˚C, 120min@60C annealing
[3] C. Fleta, RD50 Workshop June 2010, measured at -10˚C, 1d@RT or 4min@80˚C annealing
[4] M. Köhler, PhD thesis Uni Freiburg, 2011, presented at 20˚C, few days@RT annealing (not corrected for)
[5] G.F. Dalla Betta et al., NIMA 765 (2014) 155, presented at -20˚C, as irradiated (assumed 1d@RT annealing)
[6] G. Pellegrini 27th RD50 workshop + M. Baselga, PhD thesis 2016 (in prep.), measured at -20˚C, 8min@80˚C annealing

HL-LHC Studies: High Eta

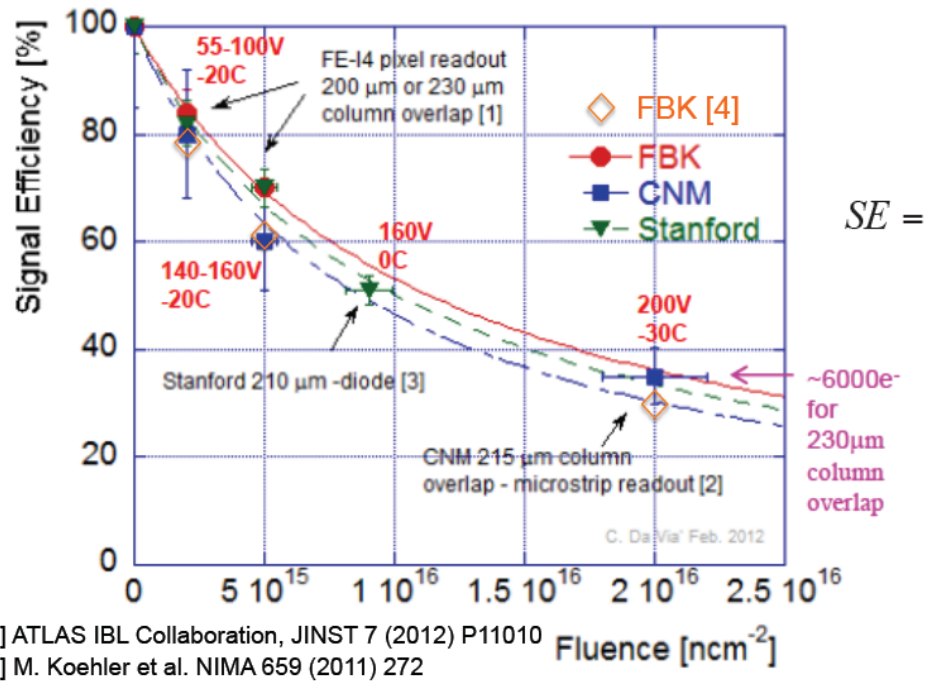
- Large clusters → large total charge → efficiency for whole cluster not a problem
- But for 50 µm pitch very small charge deposition per pixel (almost parallel tracks): 3300 e
- Testbeam campaign to measure CNM+FBK IBL FE-I4 devices with 80° angle in short pitch direction (50 µm)
  - 1000 + 1500 e threshold
  - Cluster size 24-27
  - >99% efficiency per pixel before irradiation

See talk by Ivan Lopez, RD50 Workshop June 2015

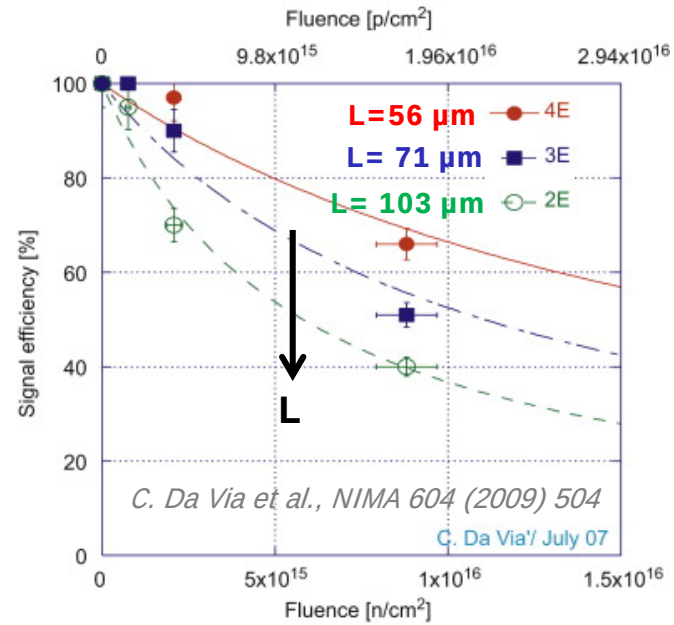
80° (η=2.4) → Q=3300 e/pixel (50 µm)



R&D Performance Summary

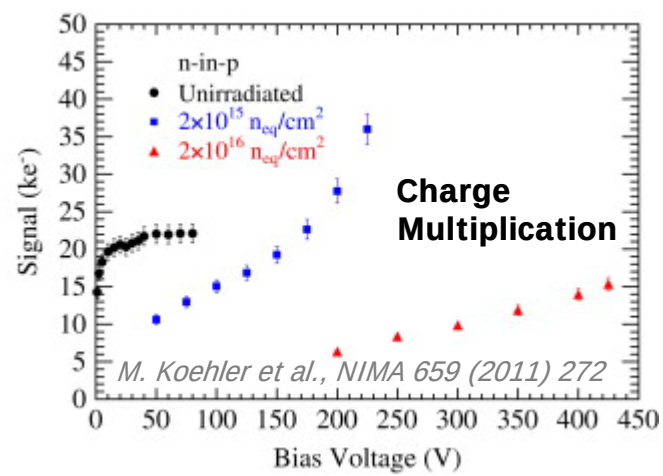


$$SE = \frac{1}{1 + 0.6L\frac{K_\tau}{v_D}\Phi}$$



[1] ATLAS IBL Collaboration, JINST 7 (2012) P11010
[2] M. Koehler et al. NIMA 659 (2011) 272
[3] C. Da Via, et al., NIMA 604 (2009) 505
[4] G.-F. Dalla Betta, et al., HSTD9 (2013)

Compilation by C. Da Via, modified by G.F. Dalla Betta



- Signal efficiency (SE) of 60-70% at 5x10^{15} n_{eq}/cm^2 and 30% at 2x10^{16} n_{eq}/cm^2 achieved for moderate V < 200 V
- Signal efficiency (SE) improves with decreasing electrode distance L
- Charge multiplication at high fluences and V can further boost collected charge