3D Silicon Pixel Detectors for HL-LHC

Emanuele Cavallaro, Fabian Förster, Sebastian Grinstein,
Jörn Lange, Iván López Paz, Maria Manna, Stefano Terzo, David Vázquez Furelos

IFAE Barcelona

Mar Carulla, Giulio Pellegrini, David Quirion

CNM-IMB-CSIC Barcelona

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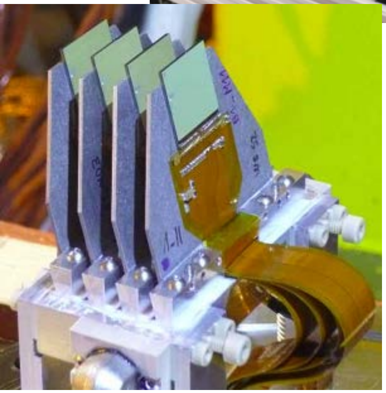
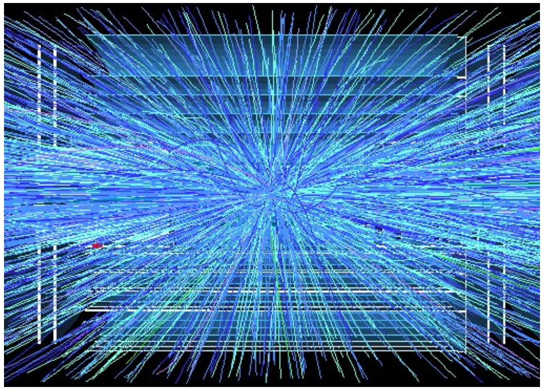
Institut de Física d'Altes Energies

EXCELENCIA SEVERO OCHOA

BIST Barcelona Institute of Science and Technology

Applications of 3D Silicon Pixel Detectors



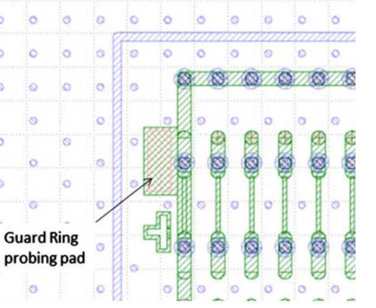


- ATLAS IBL — see Alessandro La Rosa's talk
  - 25% 3D FEI4 detectors
  - Installed during LS1 2014/15 and running since June 2015
- ATLAS Forward Proton (AFP) — see Sebastian Grinstein's talk
  - Successful 3D FEI4 module production Dec 2015- Feb 2016
  - Installed in Feb 2016 and running in LHC since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

Not covered: Diamond 3D (see Nicola Venturi's talk)

Development of HL-LHC 3D Pixel Detectors

- Properties of today's IBL/AFP generation of 3D pixel detectors
  - 230 µm thick sensors by CNM and FBK (double-sided)
  - FEI4s: 50x250 µm² 2E, 67 µm inter-el. distance
  - Radiation hardness up to 5e15 n_{eq}/cm^2 established (IBL)
  - → **Exploring limits further with irradiations up to 2e16 n_{eq}/cm^2**



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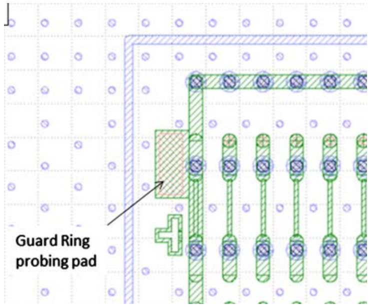
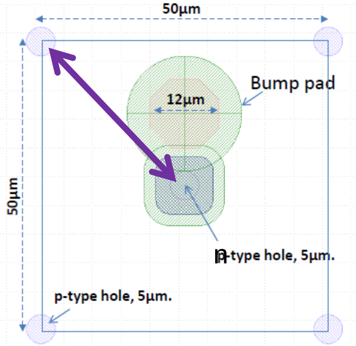


- Development of new generation of HL-LHC 3D pixel detectors
  - Radiation hardness: 2e16 n_{eq}/cm^2 required
  - Reduced pixel size: 50x50 µm² or 25x100 µm²
  - Reduced 3D inter-electrode distance L
    → less trapping, V_{dep}
    → more radiation hard
    (but higher C_{det} and more dead material)
  - Possibly reduced thickness (75-150 µm)
    → less leakage current, C_{det}, cluster size at high eta
    (but less Q at 0°, more complex production)
  - First prototype productions of new generation finished
  - → **Extensive characterisation and radiation-hardness studies on-going**

see Maurice Garcia Scivere's talk

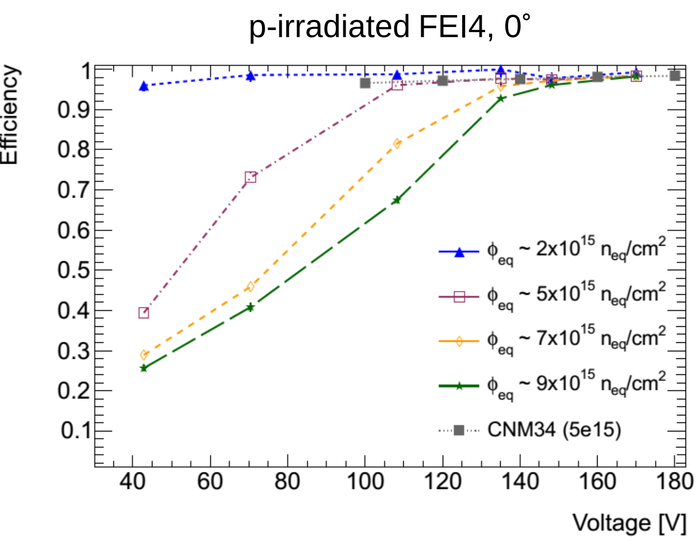
Electrode Distance L



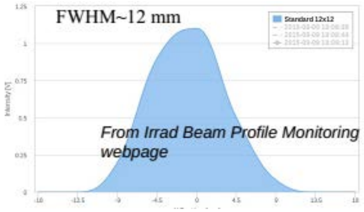
Layout	50x250 2E	50x50 1E	25x100 1E	25x100 2E
El. Dist. L	67 µm	35 µm	52 µm	28 µm

IBL FE-I4

Performance of IBL/AFP 3D Generation

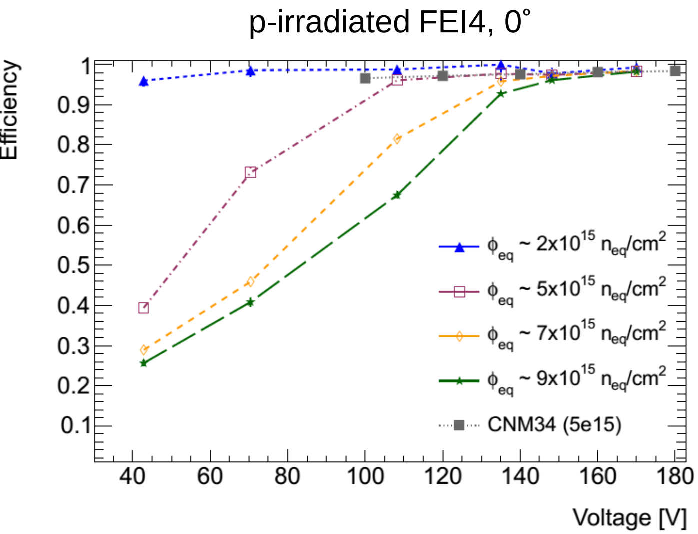


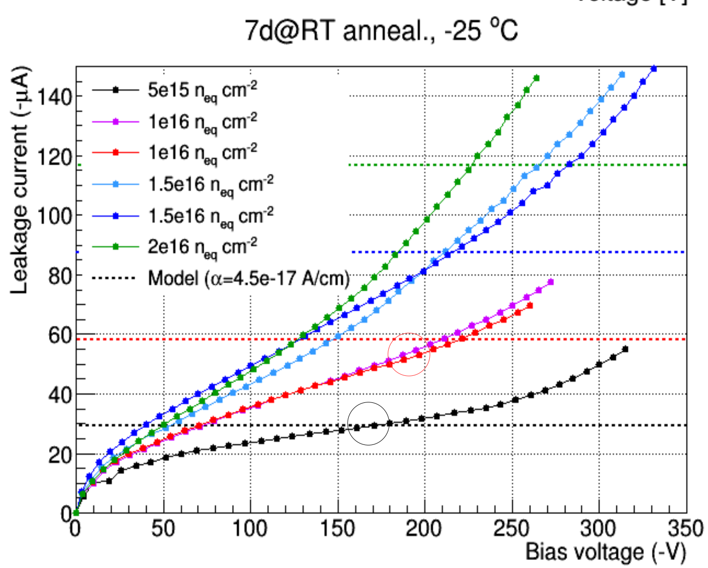
- Non-uniformly p-irradiated FEI4 (PS IRRAD)
  → probe range of fluences on single device



- 2 devices up to a peak of 9.4e16 n_{eq}/cm^2 tested in lab and beam in 2015
- **At 9.4e15 n_{eq}/cm^2: 97.8% efficiency at 170 V!**
- More devices irradiated up to a peak of 2e16 n_{eq}/cm^2 and tested in beam in 2016 (analysis on-going)

Performance of IBL/AFP 3D Generation





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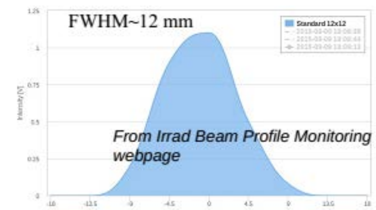

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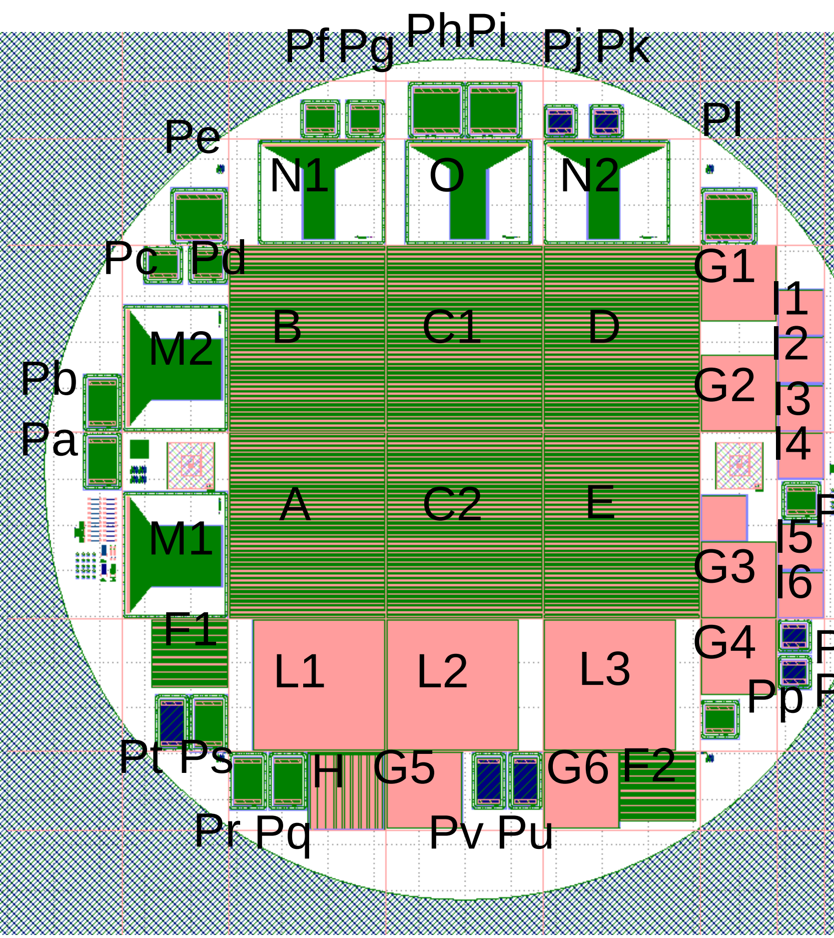
  - More devices irradiated up to a peak of 2e16 n_{eq}/cm^2 and tested in beam in 2016 (analysis on-going)

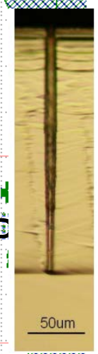
- Uniformly n-irradiated FEI3 (Ljubljana)
  - I_{leak} fluence dependence roughly as expected
  - **Power dissipation 15 mW/cm² at 1e16 n_{eq}/cm^2** for IBL-type geometry (L=71 µm, 230 µm thickness, 180 V, -25°C)
    - In climate chamber. On cold chuck even 20% less (12 mW/cm²)

→ Good performance at HL-LHC fluences even for existing 3D generation

First Small-Pixel CNM Run for HL-LHC

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





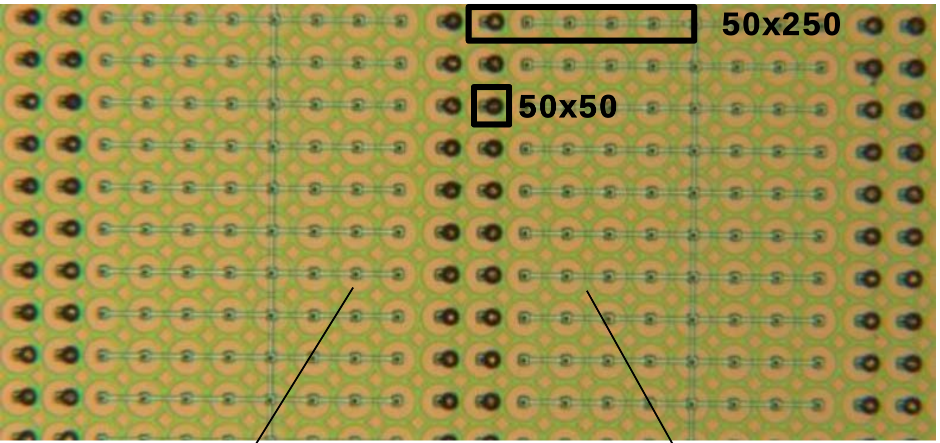
- RD50 project (in collaboration with Santander)
- Run 7781 finished in Jan 2016
- 5 wafers, p-type, 230 μm double-sided, non-fully-passing-through columns (a la IBL)
- **First time small pixel size 25x100+ 50x50 μm²** (folded into FEI4 and FEI3 geometries)
  - Also strips and diodes down to 25x25 μm² 3D unit cell
- Increased aspect ratio 26:1 (column diameter 8 μm)

Number of 3D electrodes/pixel

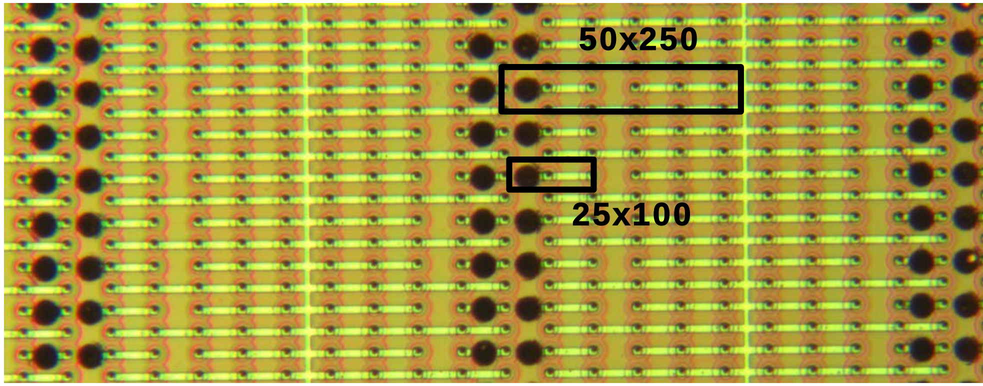
- A: 25x250 μm² 2E - standard FE-I4
- B: 25x500 μm² 5E – i.e. 5x "25x100" 1E, with 3DGR
- C: 50x50 μm² 1E with the rest connected to GND with 3DGR
- D: 25x100 μm² 2E with the rest connected to GND
- E: 50x50 μm² with the rest connected to GND without 3DGR
- F : FEI3 device: 50x50 μm² with rest to GND 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

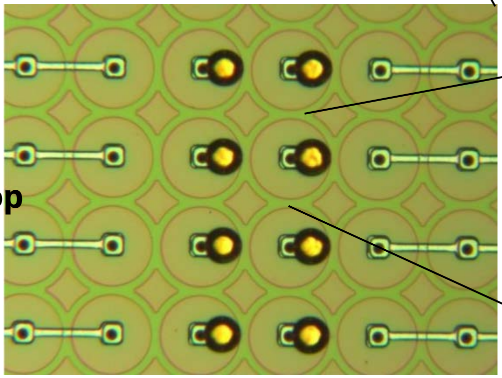
C/E: 50x50 µm² 1E
with the rest connected to GND



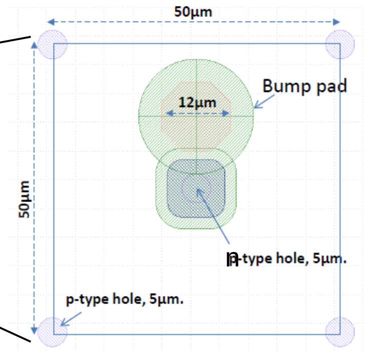
D: 25x100 µm² 2E
with the rest connected to GND



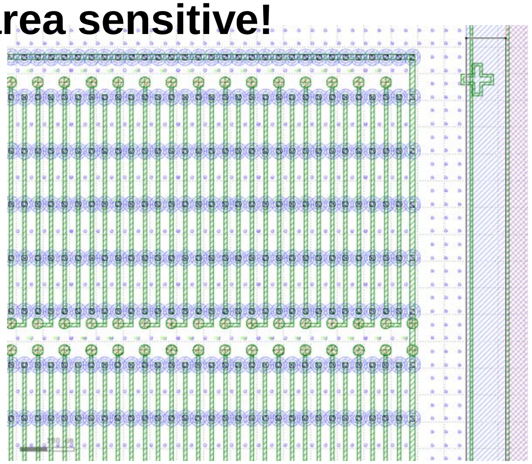
P-stop



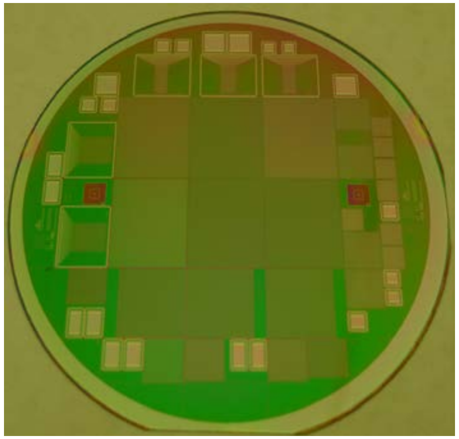
Electroless UBM



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

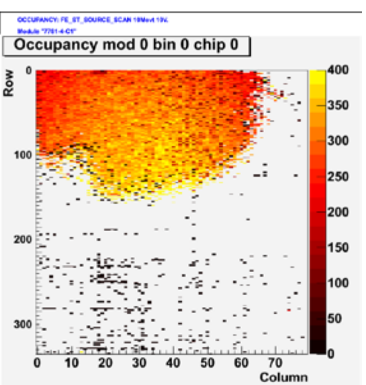


Wafer and Device Status

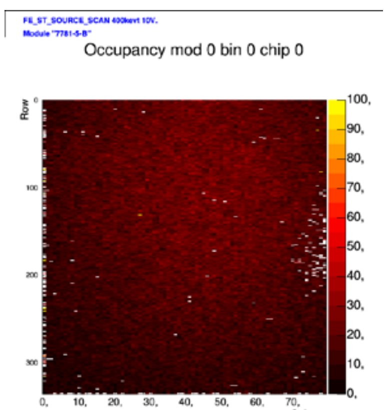


Sr90 Occupancy

Bad UBM
6 FEI4s electro-less+plate

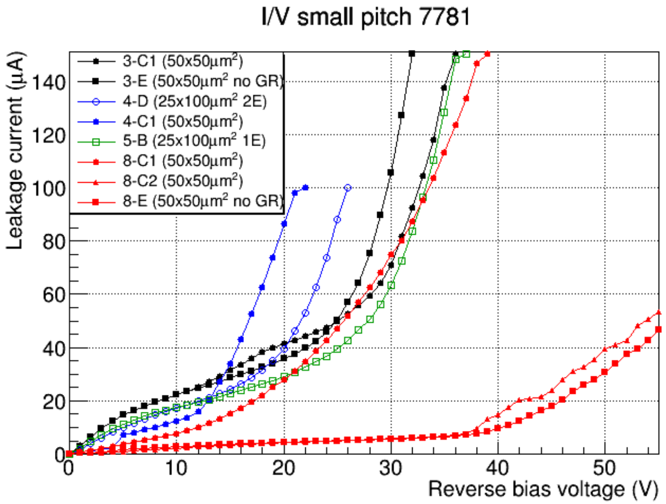


Good UBM
2 FEI4s, 1 FEI3 electro-less



- 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
  - Flip-chipped, assembled and tested at IFAE
  - Many devices have disconnected bumps, 2x chip detached from sensor, but some devices 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 (5, 10, 15, 20e15 n_{eq}/cm^2)
  - IV, CV, TCT, charge collection

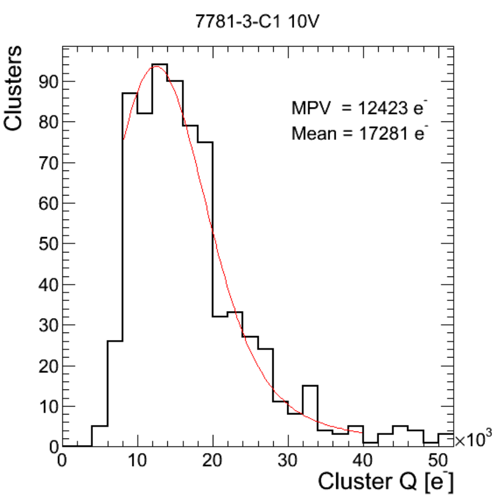
FE-I4 Pixel Characterisations

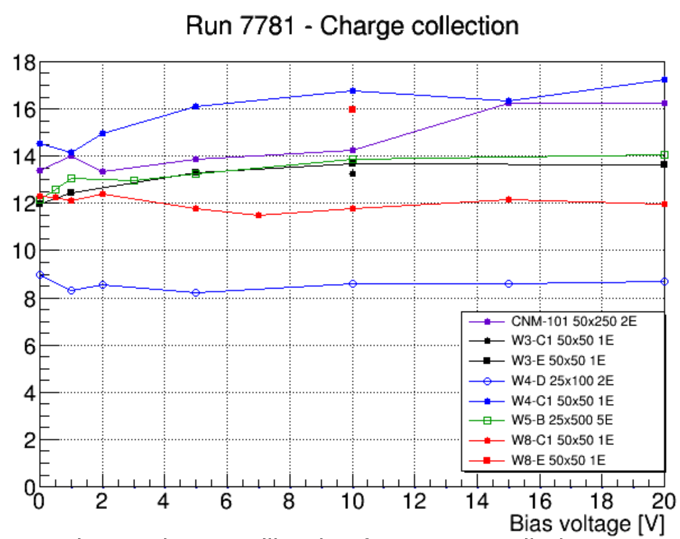


Pixel Geom.	C/el. [fF] (*)	C/pixel [fF] (*)	Noise [e]
25x100 2E	42	84	160
25x500 5E	na	na	130
50x50 1E	37	37	105-140

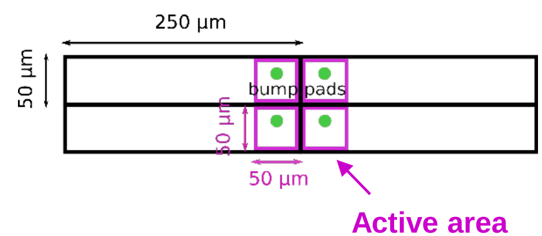
(*) from pad diodes

- 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





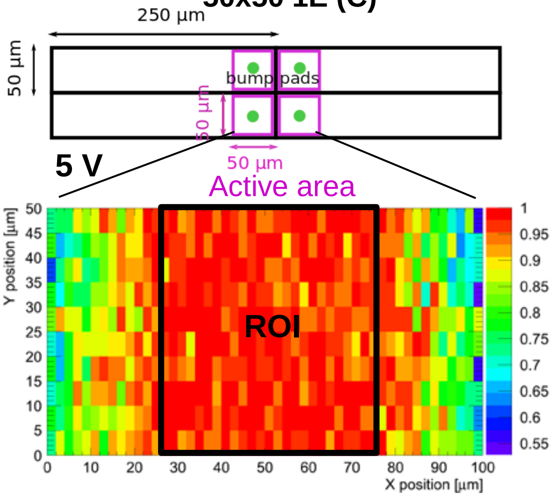
Cluster size 2, calibration factor 1.4 applied

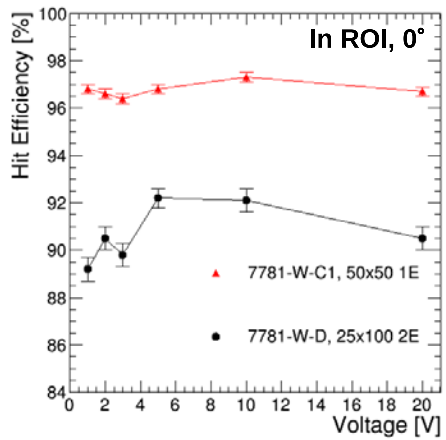


Performance in Beam Tests

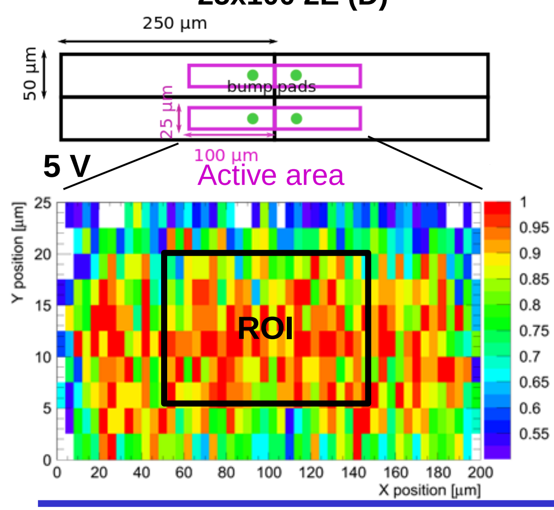
In-Pixel Efficiency (FEI4 telescope, 0°)

50x50 1E (C)

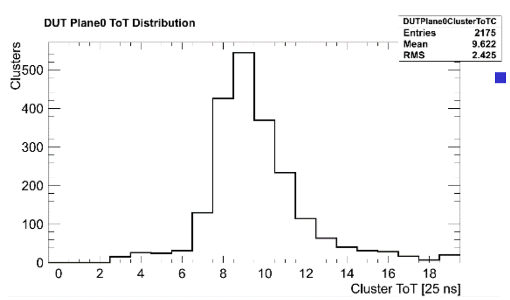




25x100 2E (D)

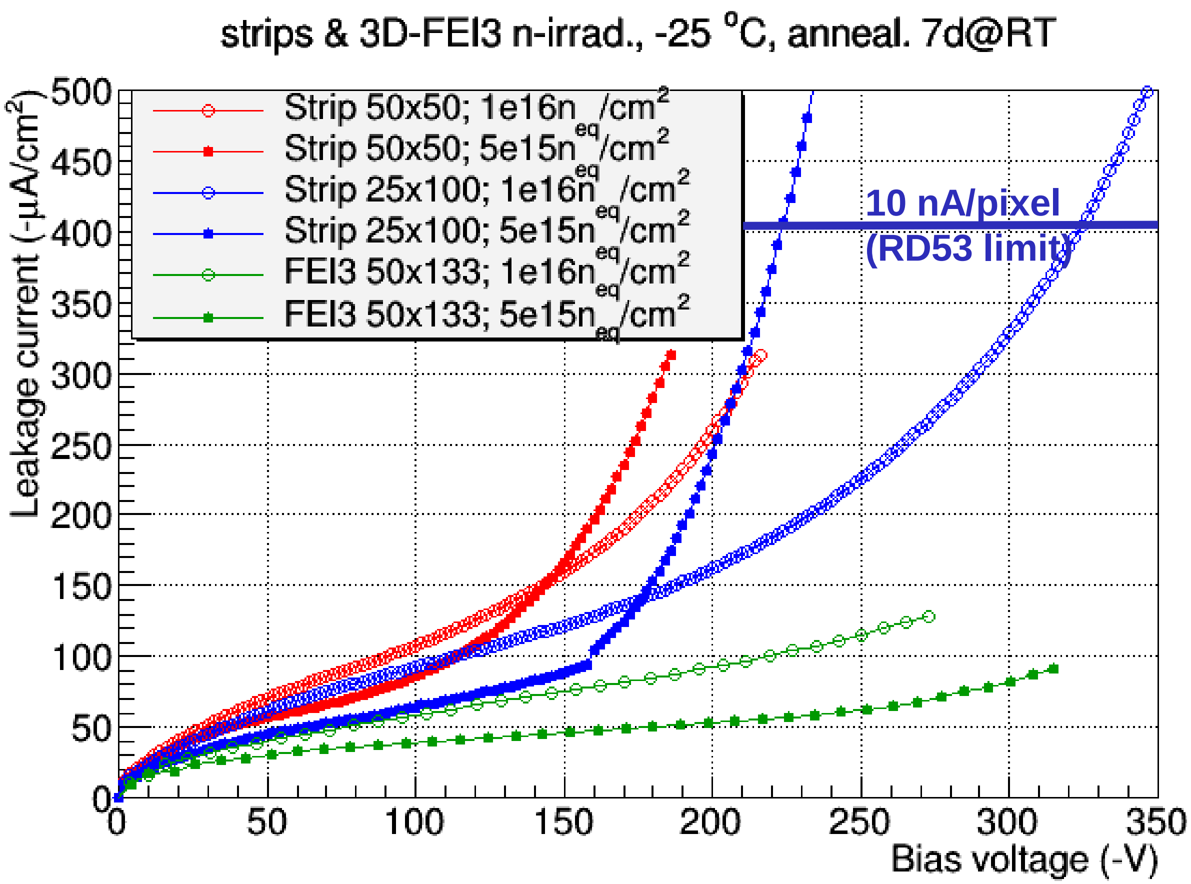


Cluster ToT



- 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% for 50x50 µm² 1E already from 1 V at 0°
  - 92% for 25x100 µm² 2E at 10V at 0°
    → Telescope res.? Or more inefficient area from larger fraction of insensitive 3D columns at 0°?
    → improvable by tilting (or reduced col. diam.)
- ToT in ROI: ~9 BXs
  - As expected for 230 µm and 10BXs@20ke tuning
- Irradiated pixels at PS IRRAD to 1e16 n_{eq}/cm^2
  - Will measure at CERN beam test next week → study efficiency at HL-LHC fluences
  - Also irradiated FEI3 at Ljubljana and FEI4 at KIT

IV after Irradiation for Different 3D Geometries

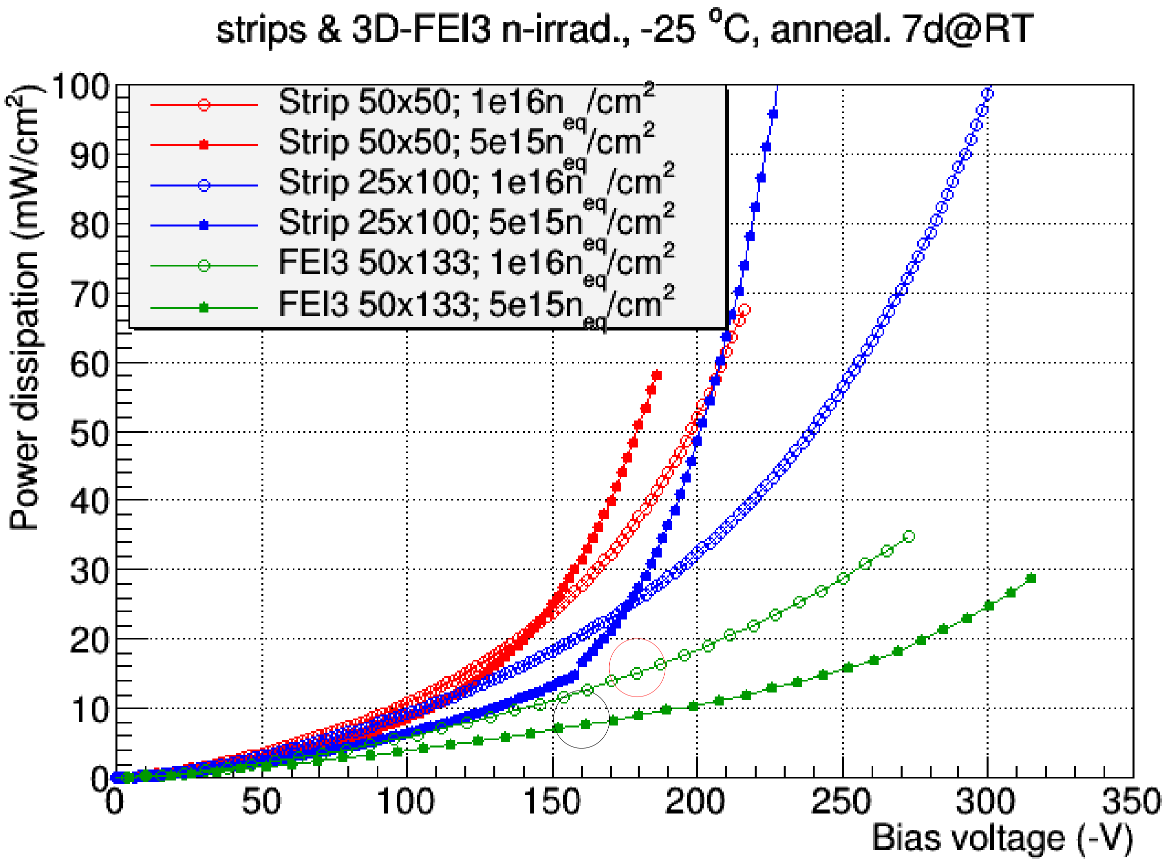


- Strip irradiation at Ljubljana
  - Results up to 1e16 n_{eq}/cm^2
  - Up to 2e16 n_{eq}/cm^2 just finished
- **Higher I_{leak} and lower V_{BD} for smaller 3D cell sizes**
- Still under investigation
  - Artifact of this run? (before CNM process optimisation)
  - Or real trend for smaller 3D cell sizes due to higher el. field and multiplication?
- Still much lower than RD53 limit of 10 nA/pixel
- **But V_{op} will be lower for smaller 3D cell sizes due to better radiation hardness**

  → compensating effect

  → V_{op} to be determined in next beam test (next week!)

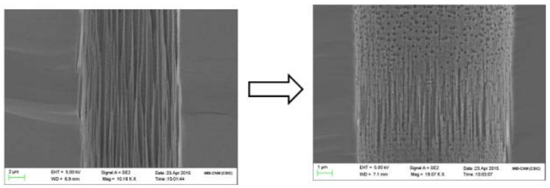
Power after Irradiation for Different 3D Geometries

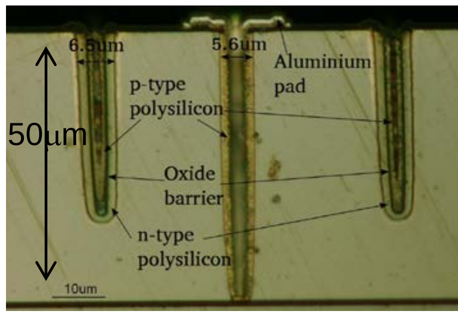


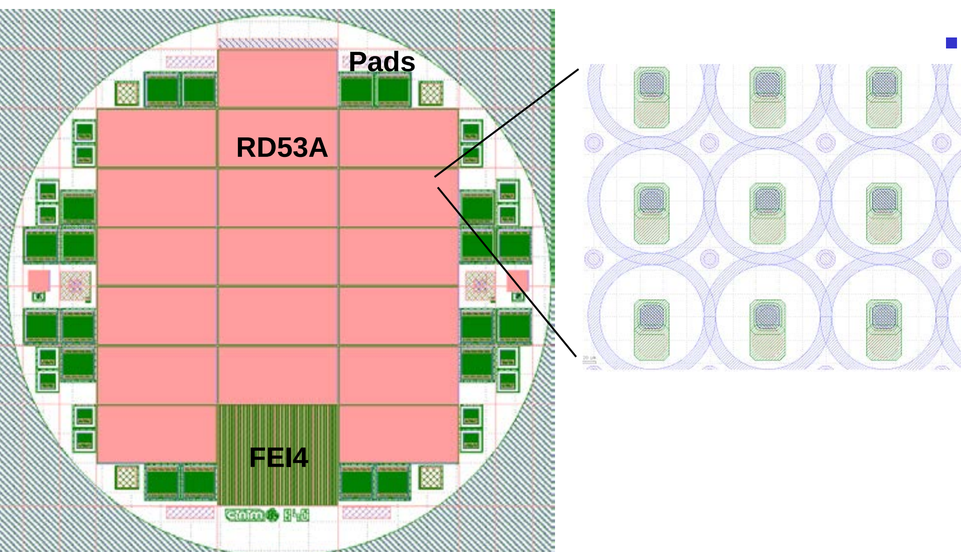
- For same V, P is higher for smaller 3D cell sizes
- **But V_{op} will be lower for smaller 3D cell sizes**
  → compensating effect for power
  → V_{op} to be determined in next beam test (next week!)
  - For example:
    for the same power dissipation as for FEI3 at 1e16 n_{eq}/cm^2 and 180 V (15 mW/cm²),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

Up-coming 3D Runs at CNM

IBL / AFP1 / 7781 → **AFP2 / CT-PPS**







- New run as copy of 7781 with improved process
  - Expect better yield and IVs (shown by AFP+CT-PPS runs)

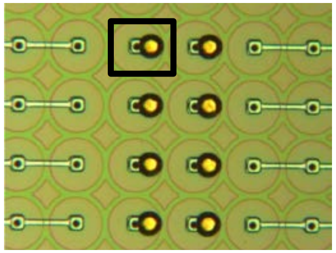
    See S. Grinstein's + F. Ravera's talks
  - Production started → expected for end of year
- Thin 3D runs (100-150 µm on SOI)
  - Already successful experience with 50 µm run at CNM
  - Same mask as recent 3D run 7781
  - Production started → expected for end of year
- Runs with RD53A pixel devices
  - Single-sided 72, 100+150 µm: masks ordered → ~1 year
  - Double-sided 200 µm planned later
  - Devices
    - 14 RD53A 50x50 µm² 1E
    - 2 RD53A 25x100 µm² 1E
    - 2 RD53A 25x100 µm² 2E
    - 1 FEI4 50x50 µm² 1E (equivalent to 7781 C)
    - Pad diodes of 50x50 µm² and 25x100 µm²

Conclusions and Outlook

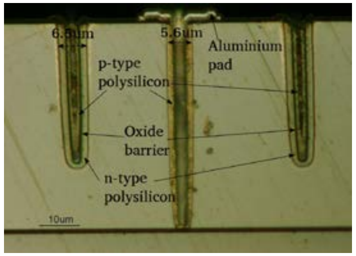
- Studied IBL/AFP-generation 3D pixel detectors up to HL-LHC fluences
  - 3D FEI4 >97% efficiency at 170 V at 9.4e15 n_{eq}/cm^2
  - Low power dissipation: 15 mW/cm^2 at 1e16 n_{eq}/cm^2 and 180 V for 230 µm (in climate chamber)

- First new-generation 3D production with small HL-LHC pixel size
  - Characterisation and beam tests of 50x50 and 25x100 µm² FEI4s performed
    - Good performance before irradiation as expected
  - Beam test with irradiated small-pixel 3Ds next week
  - Irradiation of strips 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}

50x50 µm²



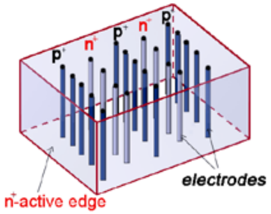
- Single-sided thin 3D and RD53-chip geometry under way at CNM
  - 72, 100 + 150 µm SOI



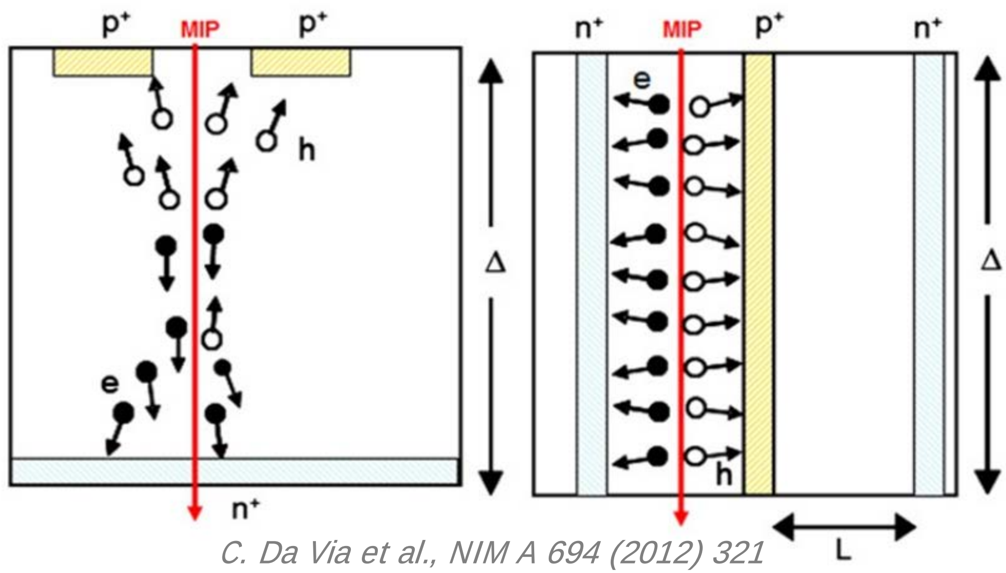
- Similar 3D development on-going at FBK Trento, SINTEF (Norway) and SLAC

BACKUP

3D Detector Principle



Planar Technology 3D Technology

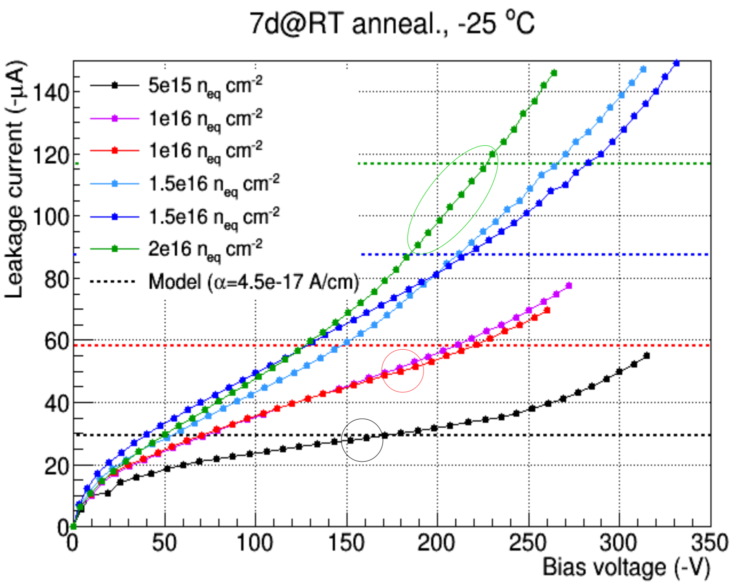


C. Da Via et al., NIM A 694 (2012) 321

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°

n-Irradiated IBL-Type FEI3



- Uniformly n-irradiated FEI3 (JSI)
  → I_{leak} measurements
  - Fluence dependence roughly as expected
    → dominated by radiation-induced bulk current
  - **Power dissipation 15 mW/cm² at 1e16 n_{eq}/cm²** at V_{op}=180 V for IBL-type geometry (L=71 µm, 230 µm thickness)

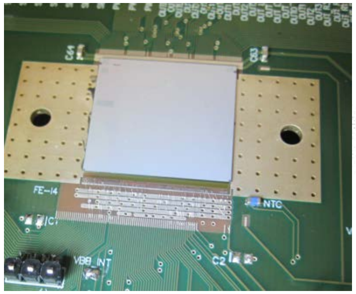
D. Vazquez (ITk Week Sep 2015)

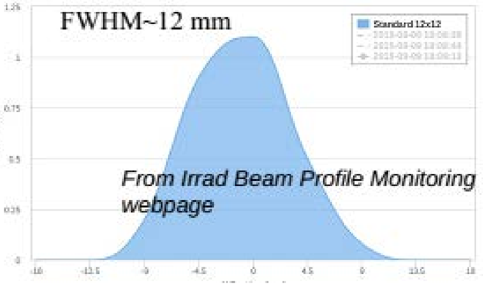
Irradiation of IBL 3D Pixels

- PS IRRAD 23 GeV p (Nov 2014 + Fall 2015)
  - FEI4 3D pixel detectors
  - Non-uniform (12 mm FWHM beam)
    → difficult for IV/power dissipation studies
  - In 2014 reached 9e15 n_{eq}/cm^2
    - Assembled at IFAE + measured in ITk beam tests
  - End 2015 further irradiation to 2.2e16 n_{eq}/cm^2 finished
    - To be assembled at CERN for May ITk beam test
    - Radiation hardness of FEI4 after p irradiation above 1e16 n_{eq}/cm^2 not clear

  → make complementary studies with neutron irradiation for more uniform irradiation and to reach higher fluence

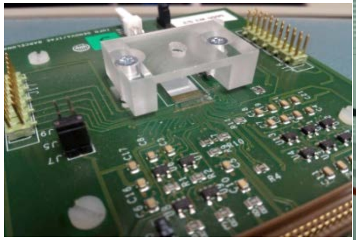
Thanks to Federico Ravotti for irradiation!





- JSI Ljubljana n (May 2015)
  - FEI4 has problem of Ta activation
    → take FEI3
  - Also have plenty FEI3s from CNM IBL wafers with great V_{BD}>100 V
  - Uniform irradiation good for IV/power dissipation study
  - Fluences:
    5e15, 1e16 (2x), 1.5e16 (2x), 2e16 n_{eq}/cm^2
  - Assembled at IFAE (bump- and wire-bond + gluing)

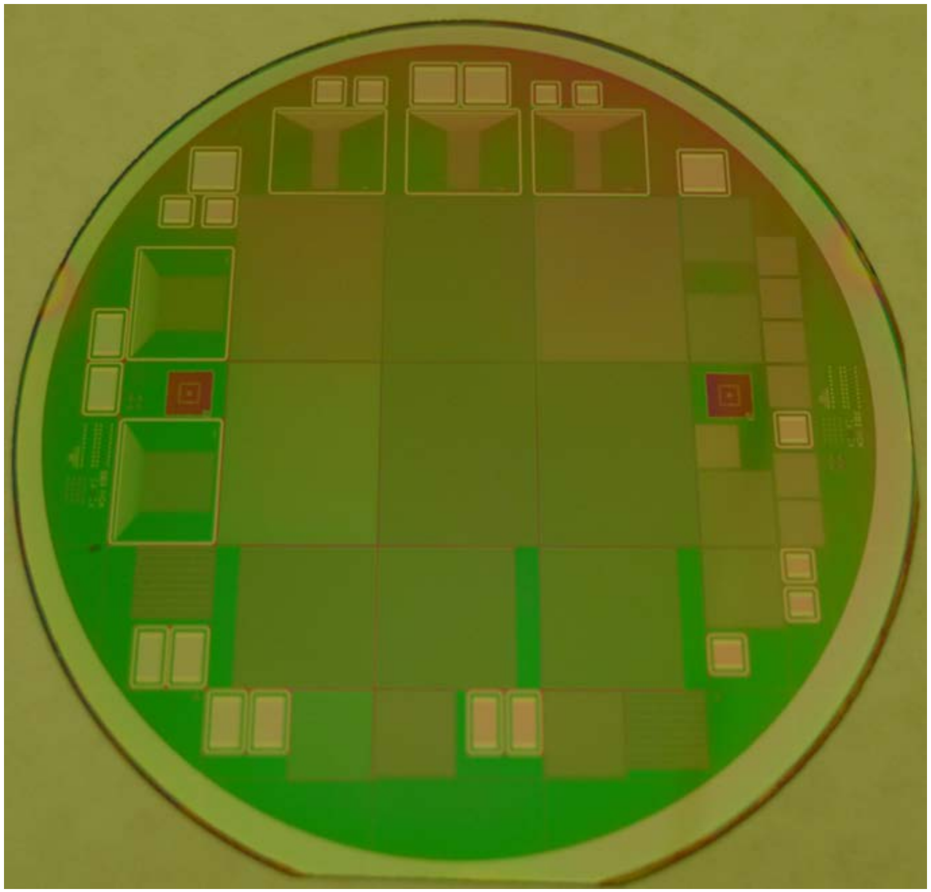
Thanks to Igor Mandic, Vladimir Cindro for irradiation and AIDA2020 support!



First time 3D pixel detectors irradiated to ITk fluences!

Wafer and Columns

G. Pellegrini, D. Quirion

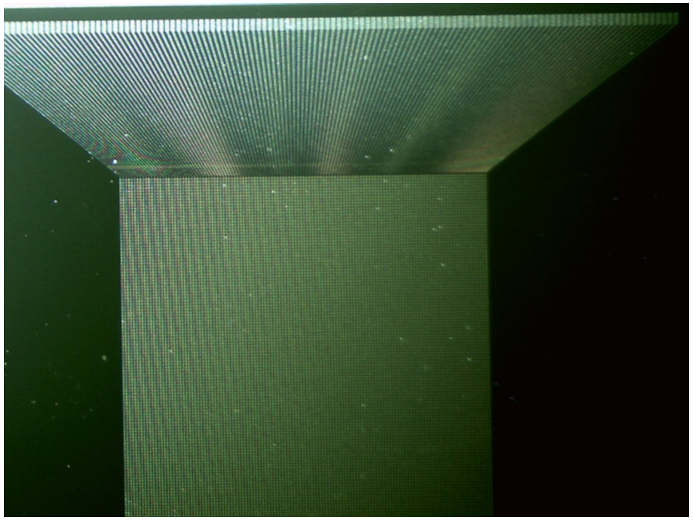


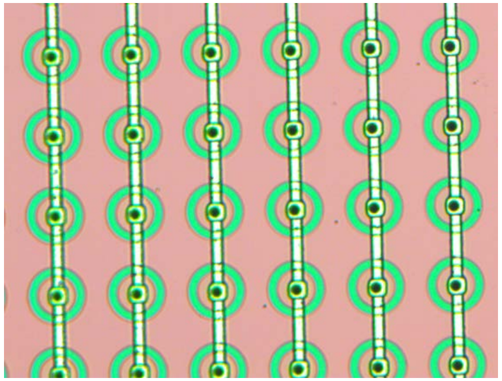
IBL	7781
3D Diameter	3D Diameter
Nominal 10 µm	Nominal 8 µm
Maximum 13 µm	Maximum 10 µm

→ **Increased aspect ratio 26:1 (nom.)**

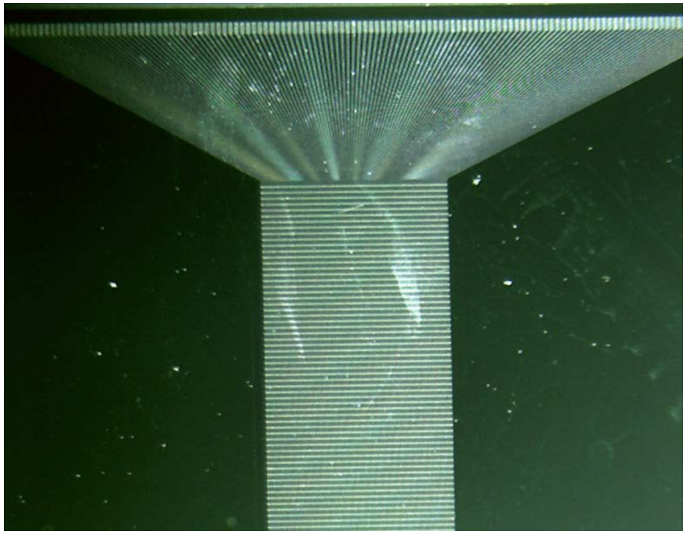
Strips

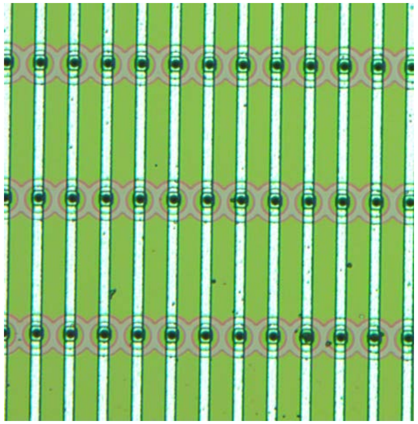
50x50 μm² 3D unit cell
128 strips, 150 3D columns each





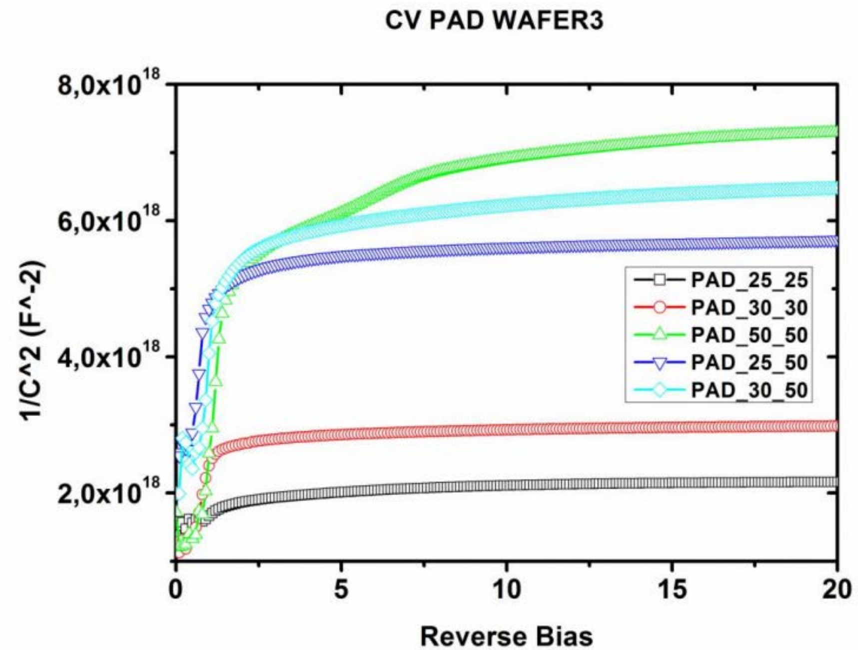
25x100 μm² 3D unit cell
128 strips, 75 3D columns each



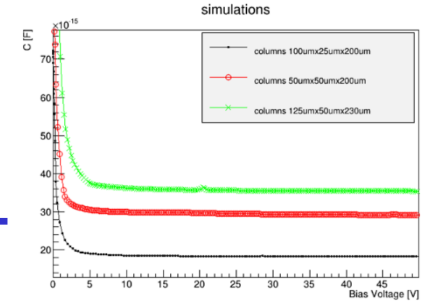


Capacitance

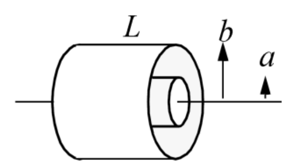
Measurements by M. Carulla



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):



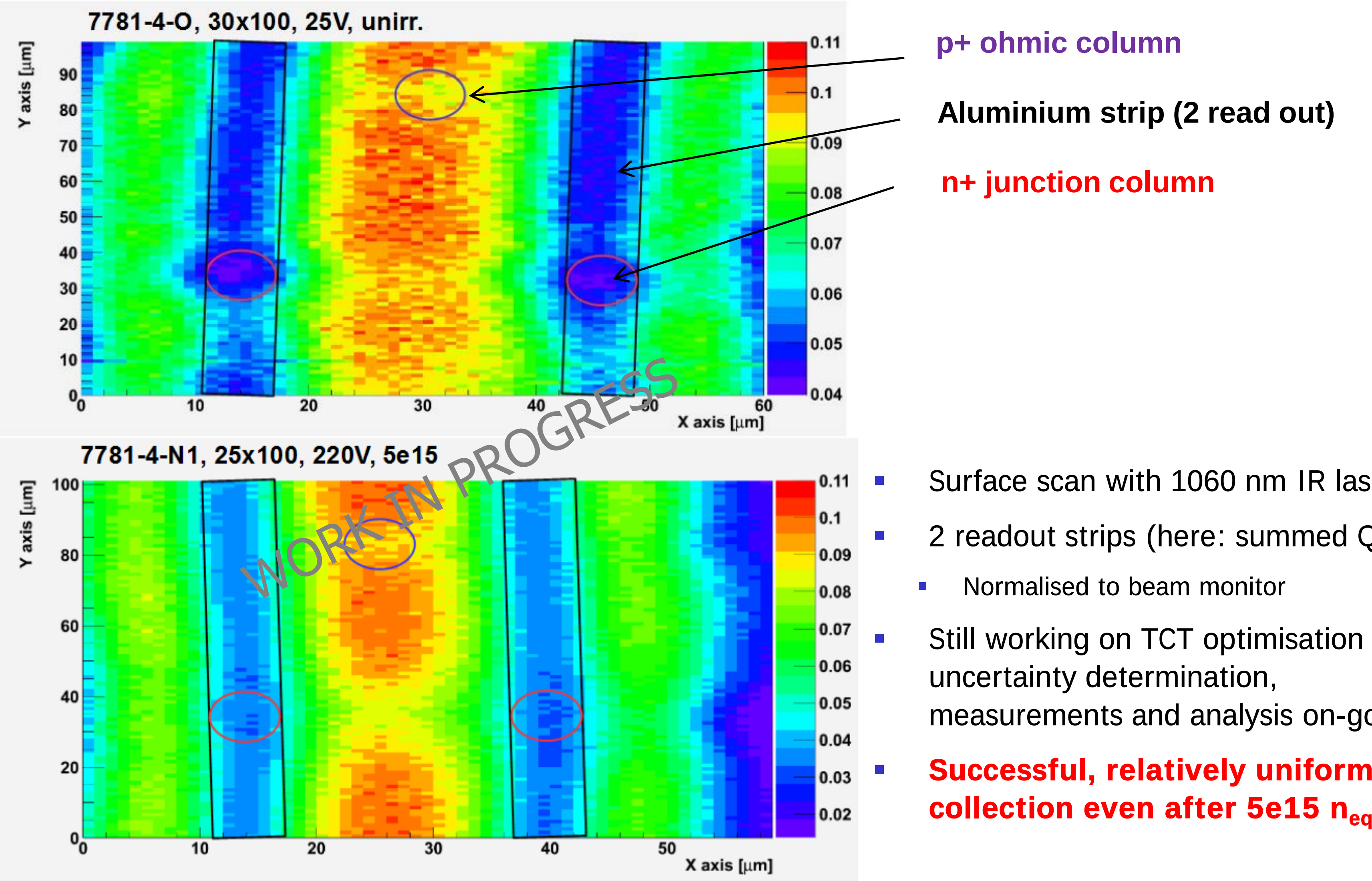
$$C = \frac{2\pi\varepsilon_0 L}{\ln\left(\frac{b}{a}\right)}$$

- 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

TCT on Strip

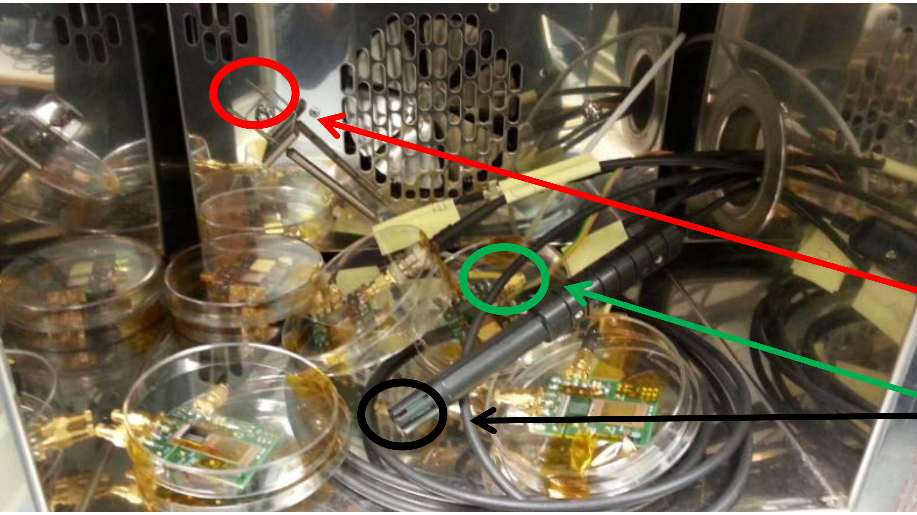
Measurements by M. Granado, L. Simon

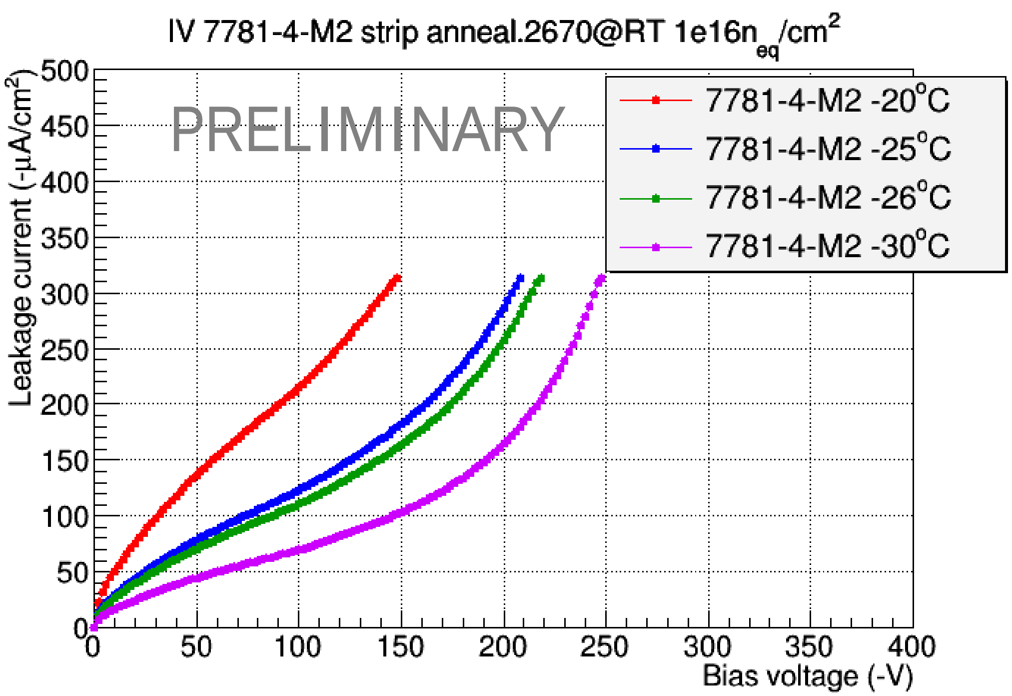


- Surface scan with 1060 nm IR laser
- 2 readout strips (here: summed Q)
  - Normalised to beam monitor
- Still working on TCT optimisation and charge uncertainty determination, measurements and analysis on-going
- **Successful, relatively uniform charge collection even after 5e15 n_{eq}/cm^2**

Leakage Current of Irradiated Strips

Measurements by D. Vazquez, E. Cavallaro, J. Lange





- IFAE climate chamber on TCT PCBs
- Standard: set to -25°C
- T monitoring
  - Climate chamber internal: -25°C
  - T meter near door: -23.8°C
  - Pt100 on sensor M2: -24.2°C

  → variation up to 1.2°C

  → 10% difference in leakage current

  → values presented here are upper limits for -25°C
- Self-heating during IV (1s/point) max. 0.2°C
- Annealing study up to 7d@RT (22-25°C)

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)

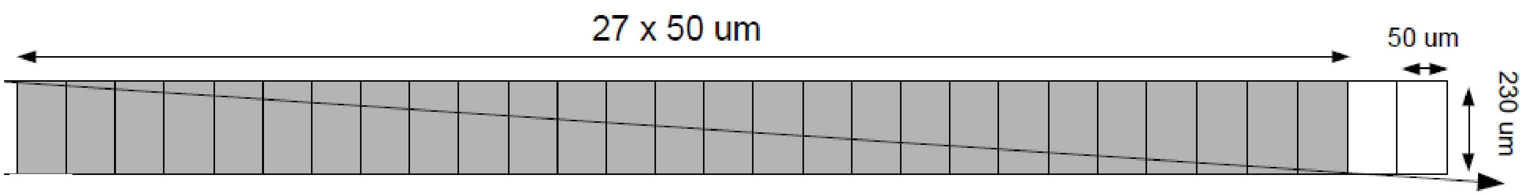
[6] G. Pellegrini 27th RD50 workshop + M. Baselga, PhD thesis 2016 (in prep.), measured at -20˚C, 8min@80˚C annealing

HL-LHC Studies: High Eta

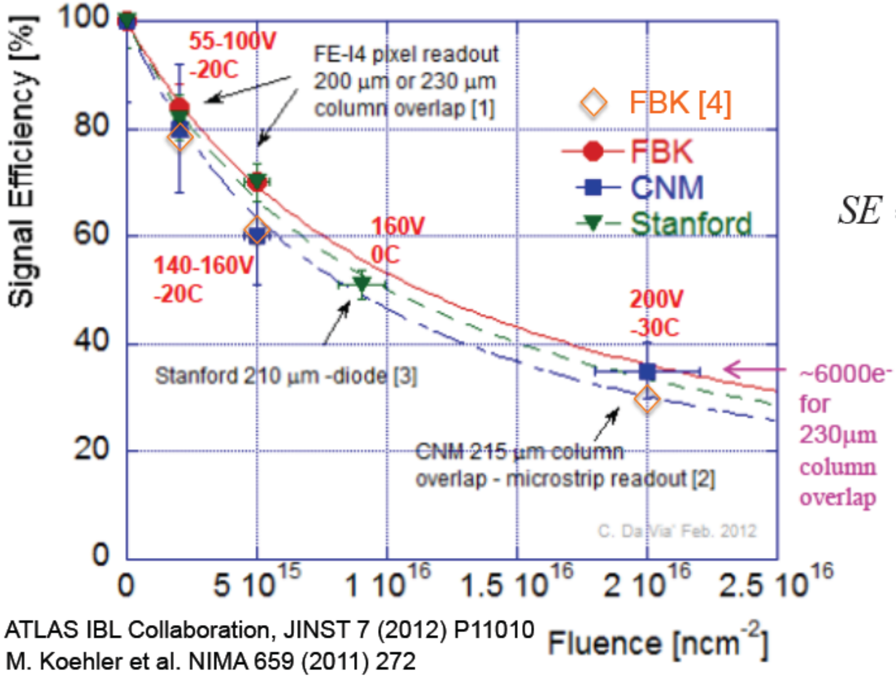
- Large clusters → large total charge → efficiency for whole cluster not a problem
- But for 50 µm pitch very small charge deposition per pixel (almost parallel tracks): 3300 e
- Testbeam campaign to measure CNM+FBK IBL FE-I4 devices with 80° angle in short pitch direction (50 µm)
  - 1000 + 1500 e threshold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

See talk by Ivan Lopez, RD50 Workshop June 2015

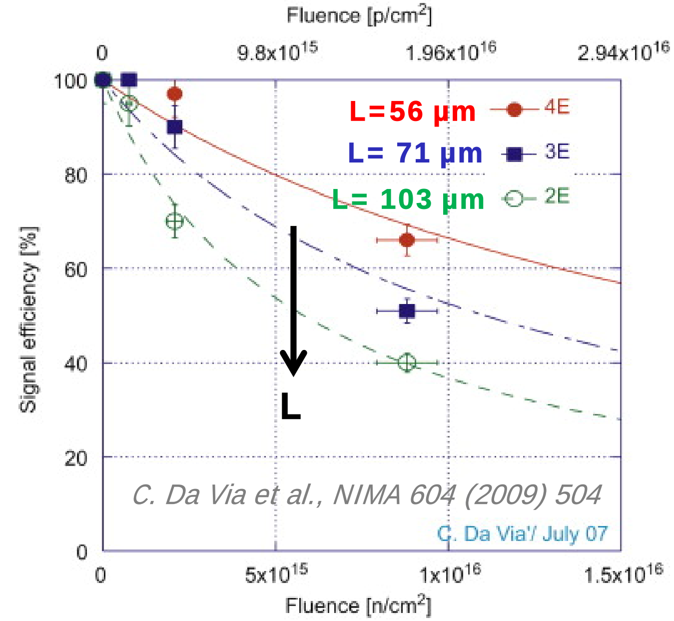
80° (η=2.4) → Q=3300 e/pixel (50 µm)



R&D Performance Summary

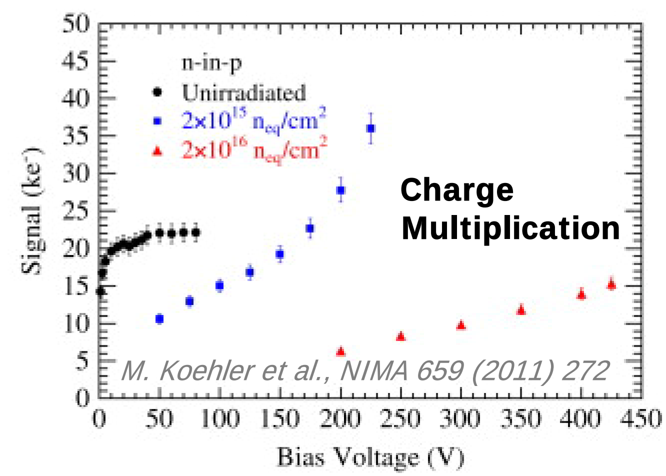


$$SE = \frac{1}{1 + 0.6 L \frac{K_\tau}{v_D} \Phi}$$



[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 5×10^{15} n_{eq}/cm^2 and 30% at 2×10^{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