3D Pixel Detectors for AFP and HL-LHC

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

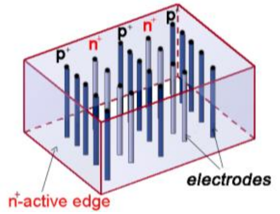
IFAE Barcelona

Giulio Pellegrini, David Quirion

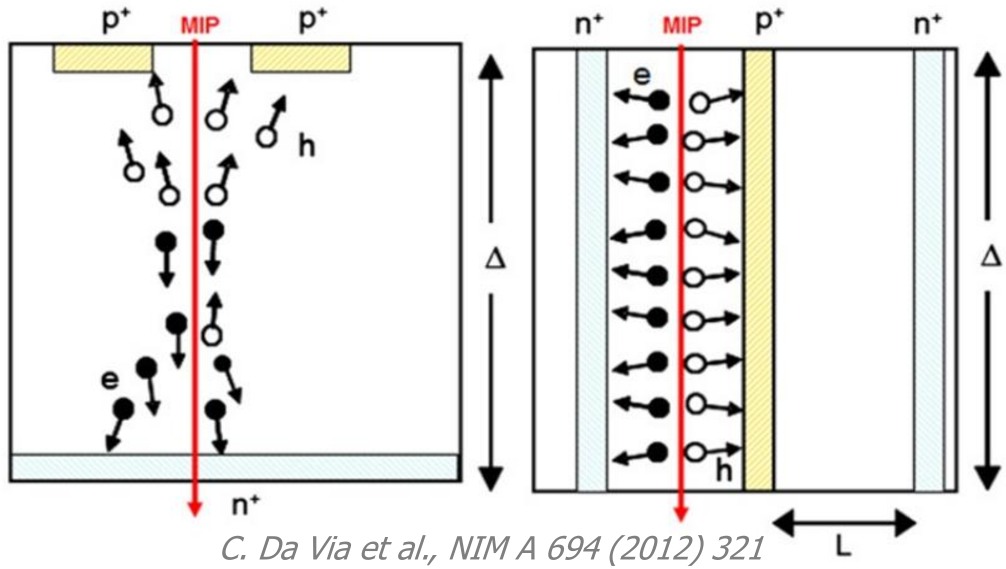
CNM-IMB-CSIC Barcelona

28th RD50 Workshop, Torino, 6-8 June 2016

3D Detector Principle



Planar Technology 3D Technology

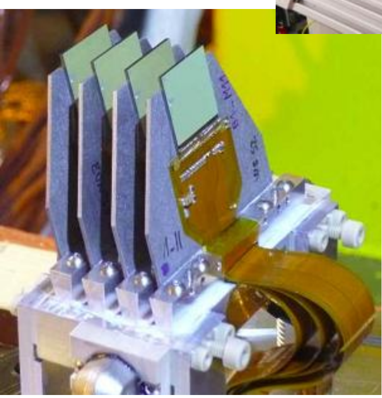


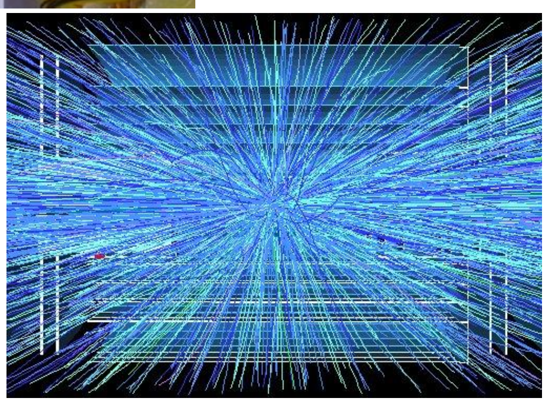
C. Da Via et al., NIM A 694 (2012) 321

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°

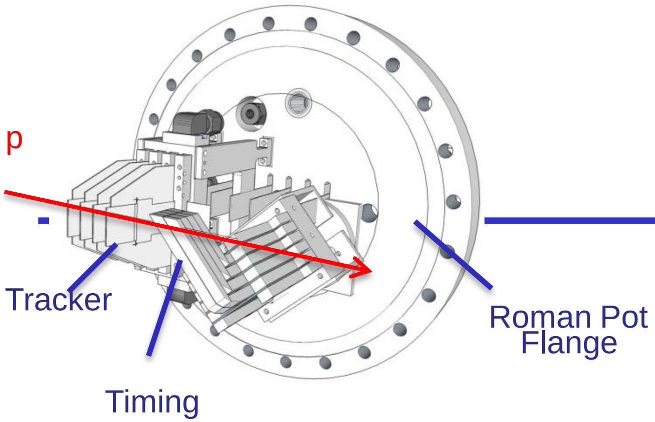
Applications of 3D Pixel Detectors



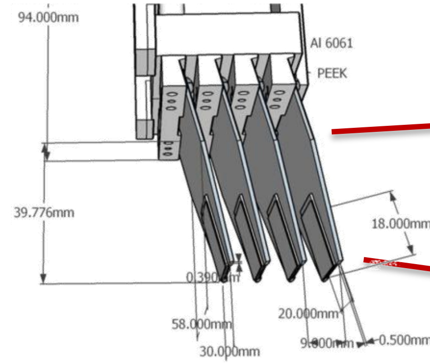


- ATLAS IBL
  - 25% 3D FEI4 detectors
  - Installed during LS1 2014/15 and running since June 2015
- ATLAS Forward Proton (AFP)
  - Successful 3D FEI4 module production Dec 2015- Feb 2016
  - Installed in Feb 2016 and running in LHC since March 2016
- CMS-TOTEM PPS
  - Sensors produced, installation planned this year
- HL-LHC pixel detectors
  - Possible installation 2024, sensor qualification for Pixel TDRs 2017
  - Radiation hardness studies with IBL/AFP 3D FEI4 generation on-going
  - First dedicated 3D sensors with small pixel size and inter-electrode distance produced and characterised

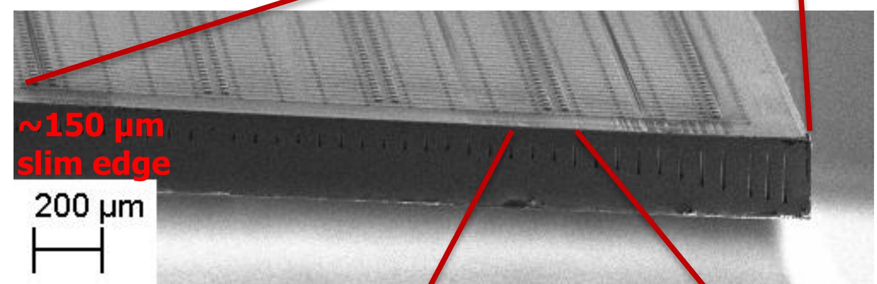
AFP Tracker



- ATLAS Forward Proton Detector
  - Tag and measure forward protons
  - Tracker + Time of Flight in Roman Pots
  - **One arm (0+2 stations) installed** in YETS 2015/16
  - Second arm (2+2) planned for EYETS 2016/17
- Tracker Station
  - 4 planes of 3D CNM FE-I4 Si pixel sensors (ATLAS-IBL proven)
  - 14° tilt in x for efficiency and resolution improvement
- Requirements
  - Slim edge 100-200 µm
    - Achieved 15-150 µm in tests
  - Radiation hard after non-uniform irradiation
    - Demonstrated up to peak of 4e15 n_{eq}/cm^2
  - 10 (30) µm resolution in x (y)
    - Achieved 3 µm/station in x



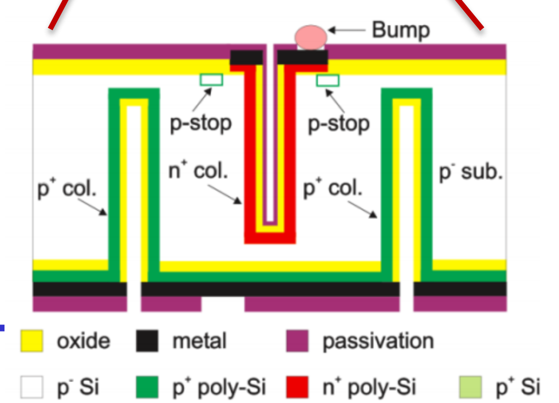
3D FEI4 Pixels



Presentations at various RD50 Workshops

S. Grinstein et al., NIM A730 (2013) 28

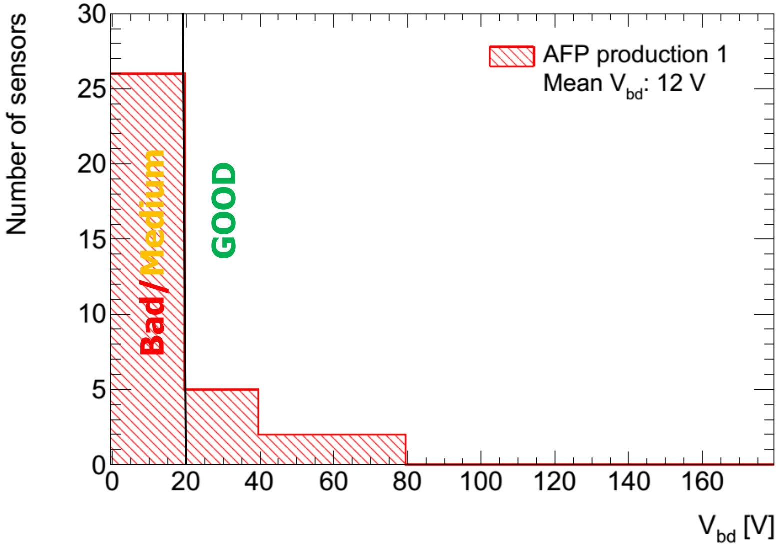
J. Lange et al., JINST 10 (2015) C03031



AFP Sensor Production

- 1st CNM AFP production run 6682 (July 2014)
  - 5 wafers with 40 sensors successfully finished, 8 wafers lost
  - Slim-edged to 180 µm
  - 9 good-quality sensors → low yield

→ This is all we had for the first AFP pixel module production and installation in 2015/2016



Production Run	Wafer Yield	Good Wafers	Sensor Yield	Good Sensors
AFP 1 (6682)	38%	5	23%	9

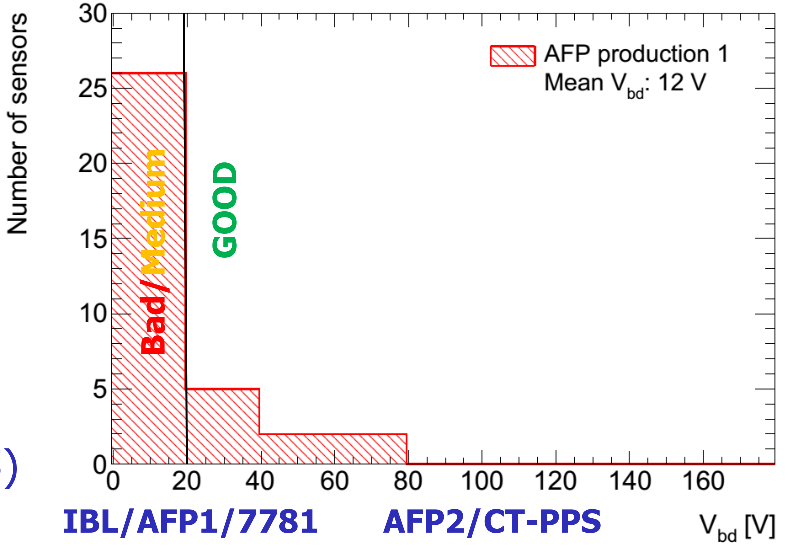
Good sensor: $V_{BD} > 20$ V
Sensor yield based on good wafers

AFP Sensor Production

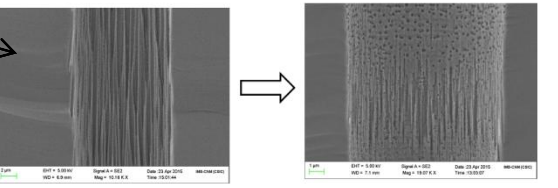
- 1^{st} CNM AFP production run 6682 (July 2014)
  - 5 wafers with 40 sensors successfully finished, 8 wafers lost
  - Slim-edged to 180 µm
  - 9 good-quality sensors → low yield

→ This is all we had for the first AFP pixel module production and installation in 2015/2016

- Investigation and improvement of CNM process (2015)
  1. DRIE optimisation → less 3D side wall defects
  2. Wafer edge protection → less broken wafers



IBL/AFP1/7781 AFP2/CT-PPS



G. Pellegrini, D. Quirion

Production Run	Wafer Yield	Good Wafers	Sensor Yield	Good Sensors
AFP 1 (6682)	38%	5	23%	9

Good sensor: $V_{BD} > 20$ V
Sensor yield based on good wafers

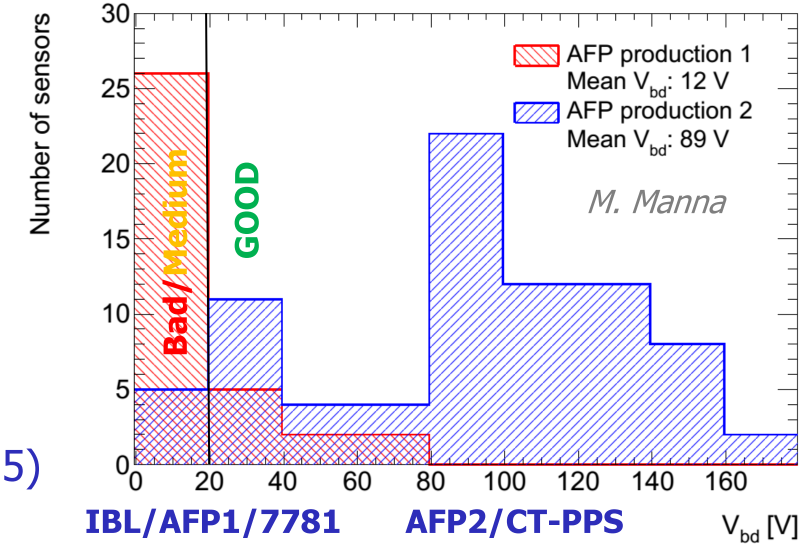
AFP Sensor Production

- 1st CNM AFP production run 6682 (July 2014)
  - 5 wafers with 40 sensors successfully finished, 8 wafers lost
  - Slim-edged to 180 μm
  - 9 good-quality sensors → low yield

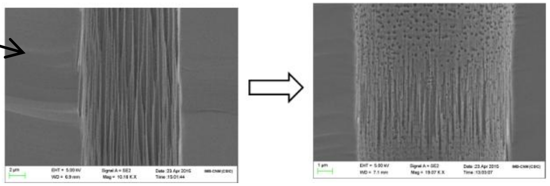
→ This is all we had for the first AFP pixel module production and installation in 2015/2016

- Investigation and improvement of CNM process (2015)
  1. DRIE optimisation → less 3D side wall defects
  2. Wafer edge protection → less broken wafers
- 2nd CNM AFP production run 7945 (March 2016)
  - 10 wafers with 80 sensors successfully finished , 2 wafers lost
  - 73 good-quality sensors
  - Sent to IZM for UBM

→ **Huge yield and IV improvement promising for 2nd arm (and HL-LHC productions)**



IBL/AFP1/7781 AFP2/CT-PPS



G. Pellegrini, D. Quirion

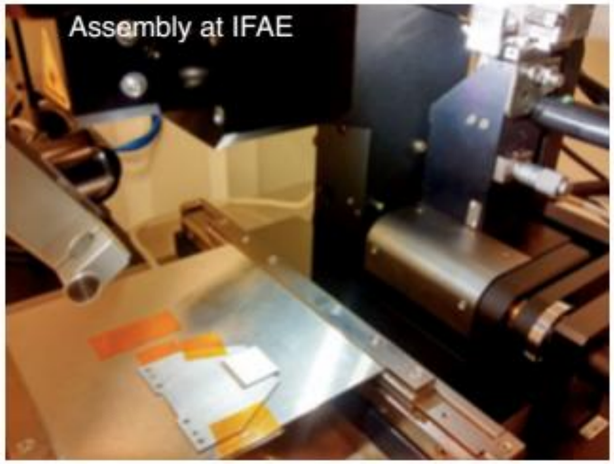
Production Run	Wafer Yield	Good Wafers	Sensor Yield	Good Sensors
AFP 1 (6682)	38%	5	23%	9
AFP 2 (7945)	**83%**	10	**94%**	73

Good sensor: V_{BD} > 20 V
Sensor yield based on good wafers

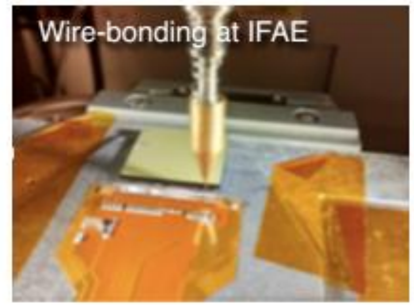
AFP Pixel Module Production

Carrier card

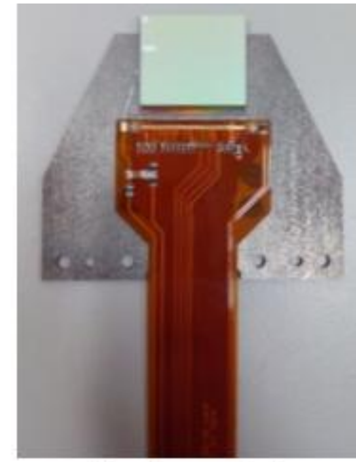
Flex



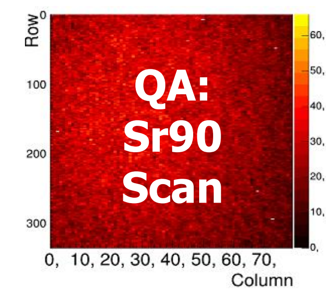
Pick and Place machine



Wire-bond machine


Tracker module

J. Garcia, E. Peregrina, S. Grinstein, M. Chmeissani



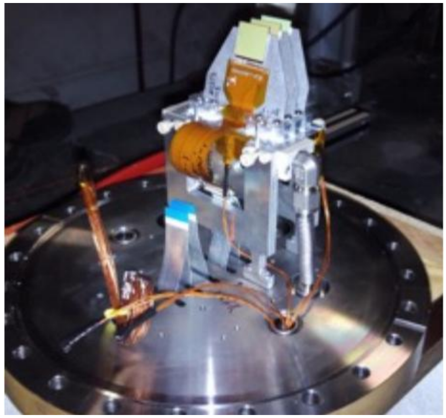
- Bump-bonding and assembly performed at IFAE
  - In-house solder flip-chipping of sensor to chip
  - Checking for disconnected bumps with X-ray
  - Hybrid is placed with pick-and-place and glued with Araldite 2011 1:1+Tesa onto NOVAPACK Al+CF carrier card
  - Flex (produced by Oslo) also glued onto carrier card
  - Chip is wire-bonded to flex (checked with pull test)
- Quality assurance (QA) at IFAE and after shipping to CERN
  - Analog/digital, tuning, Sr90 source scan

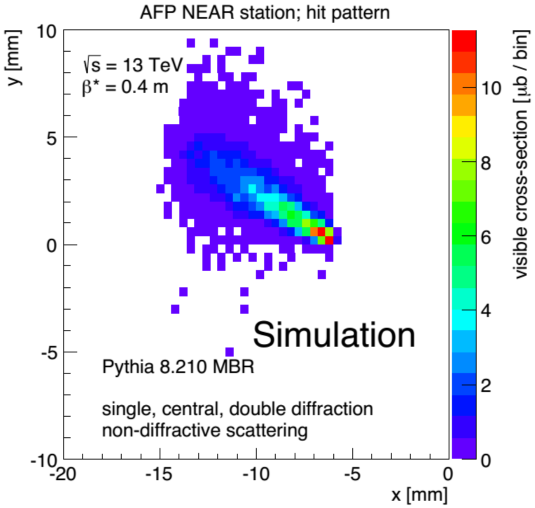
Production Step	Total	Good	Yield
Bump Bonding	22	21	95%
Assembly	17	17	100%
QA	17	14	82%

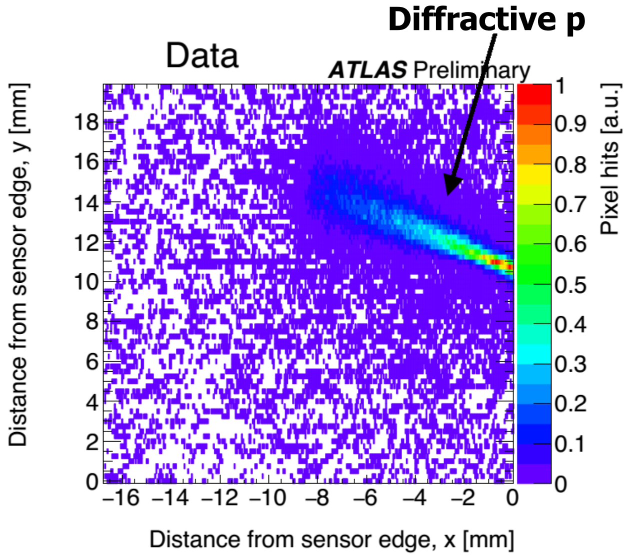
F. Förster, I. Lopez Paz

AFP Tracker Installation and Running

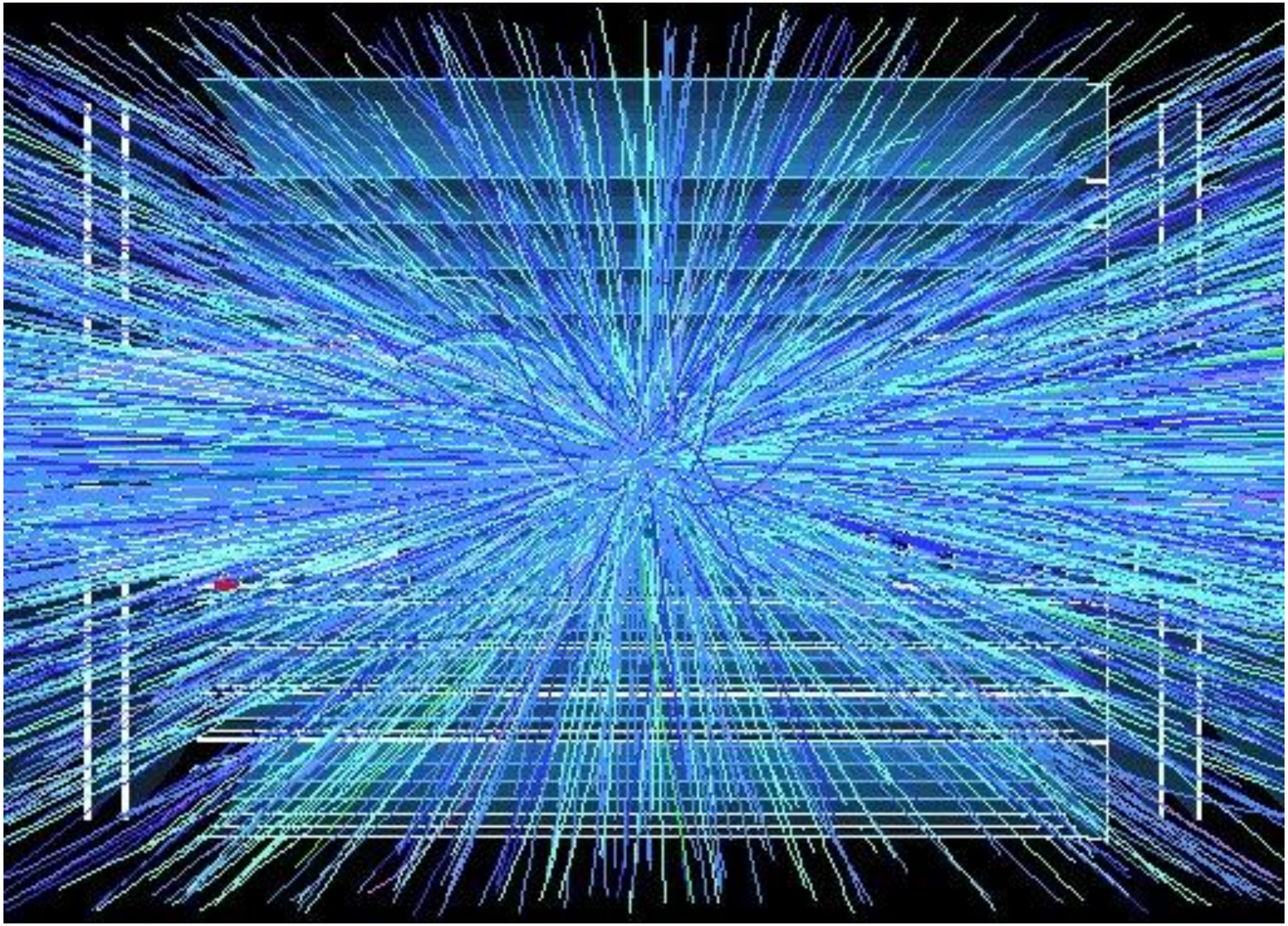
- Tracker assembled and installed in 2 Roman Pots in Feb 2016
  - NEAR station: 3 modules with V_{op}=5-10 V (not more available at that time)
  - FAR station: 4 modules with V_{op}=0-30 V (one with HV short, but 3D even at 0 V quite efficient)
- Running from the start-up of LHC in March 2016
  - Stand-alone and integrated with ATLAS, up to 600 bunches
  - **Good-quality LHC data**
- Preparing for second production phase for AFP 2+2 completion in EYETS 2016/17 (16 modules)
  - Expect further improvement in module quality due to better sensors and experience gained







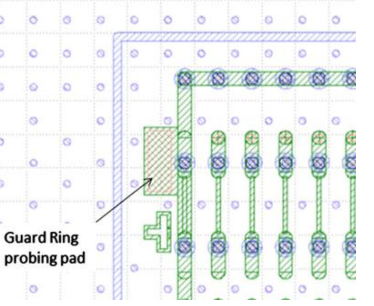
Development of HL-LHC 3D Pixel Detectors



Development of HL-LHC 3D Pixel Detectors

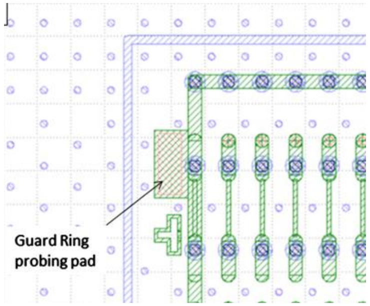
- Properties of today's IBL/AFP generation of 3D pixel detectors
  - 230 μm thick sensors by CNM and FBK
  - FEI4s: 50x250 μm 2E, 67 μm inter-el. distance
  - Radiation hardness up to 5e15 n_{eq}/cm^2 established (IBL)

→ **Exploring limits with irradiations up to 2e16 n_{eq}/cm^2**



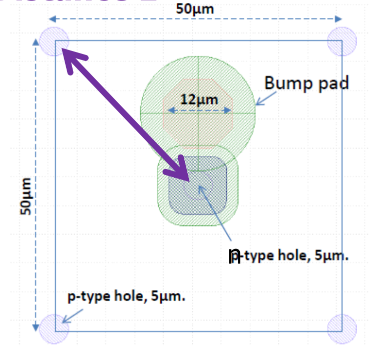
Development of HL-LHC 3D Pixel Detectors

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



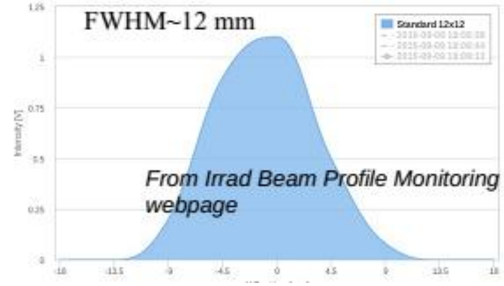
- Development of new generation of HL-LHC 3D pixel detectors
  - Radiation hardness: 2e16 n_{eq}/cm^2 required
  - Reduced pixel size: 50x50 µm² or 25x100 µm²
  - Reduced 3D inter-electrode distance L
    → less trapping, V_{dep}
    → more radiation hard
    (but higher C_{det} and more dead material)
  - Possibly reduced thickness (100-150 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**

Electrode Distance L



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

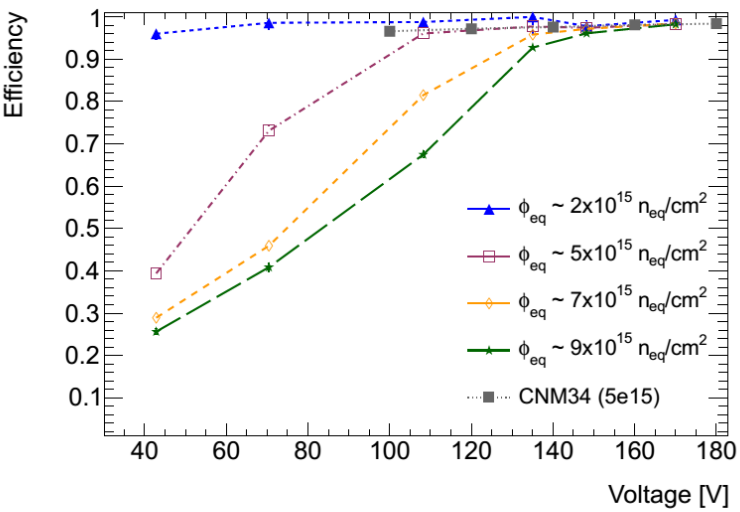
IBL FE-I4



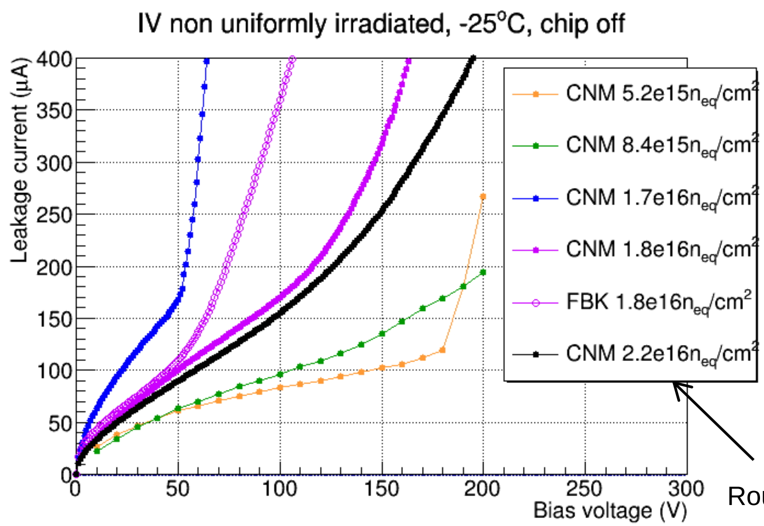
p-irradiated IBL-Type FEI4

- Non-uniformly p-irradiated FEI4 (PS IRRAD)
  → probe range of fluences on single device
- Phase 1: 12 mm FWHM beam up to peak of 9e15 n_{eq}/cm^2
  - Extracted 2 devices for characterisation and beam tests in 2015
  - **At 9.4e15 n_{eq}/cm^2: 97.8% efficiency at 170 V!**

    see I. Lopez (RD50 Workshop Dec. 2015)



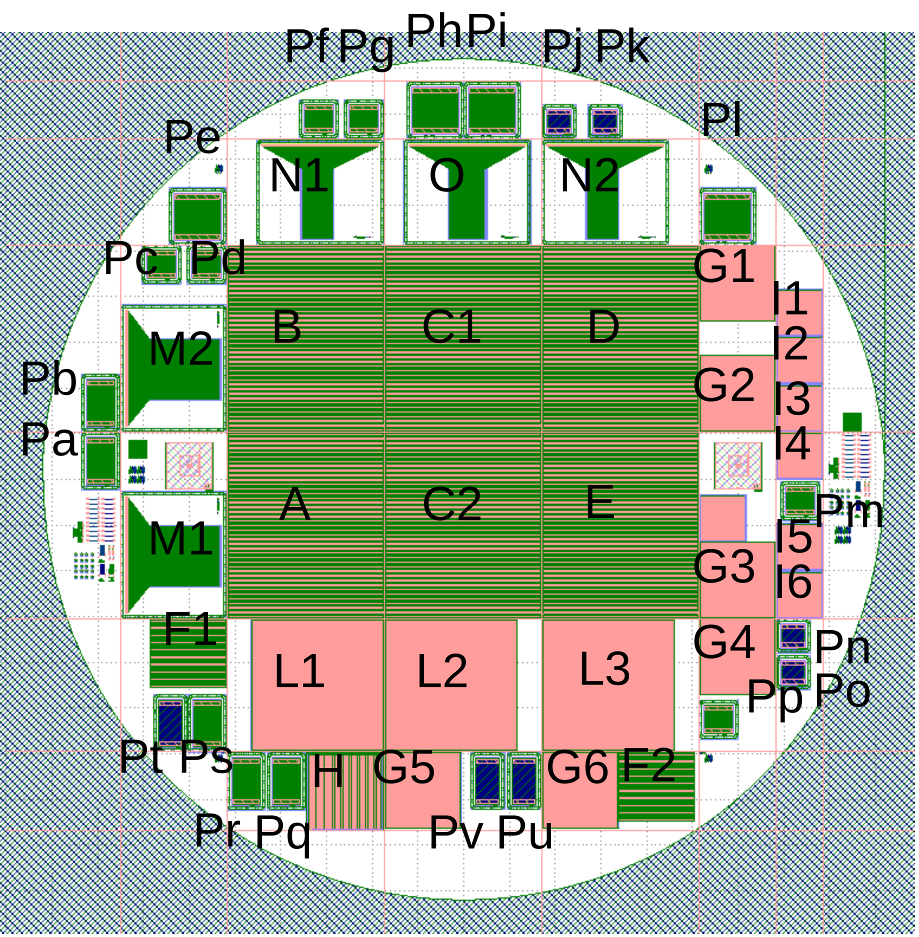
- Phase 2: Further irradiation of remaining devices with 12 or 20 mm FWHM beam up to peak of 2.2e16 n_{eq}/cm^2
  - Assembled and characterised at IFAE during last weeks
    - Devices alive, but some have chip issues (high LV current, column errors)
    - High I_{leak}, but 2 devices operable at 150-200 V
  - Beam test campaigns on-going



Rough preliminary estimate of peak (NOT mean) of non-uniform fluence

First Small-Pixel CNM Run - Overview

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



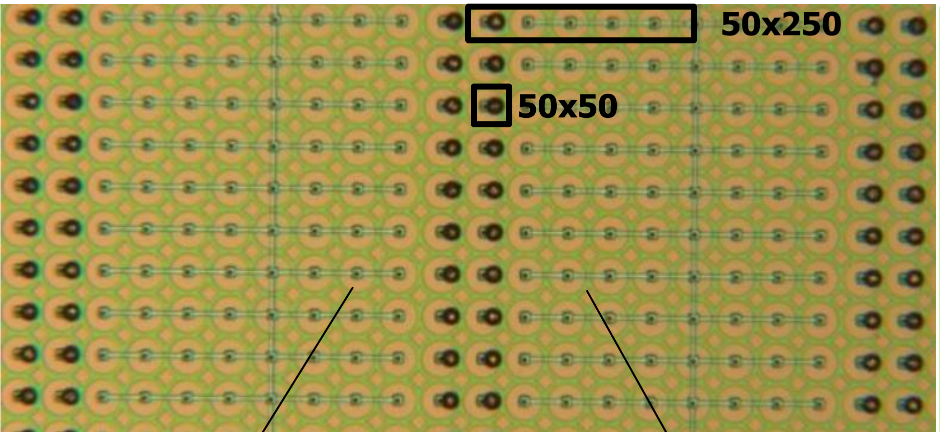
- RD50 project (in collaboration with Santander)
- Run 7781 finished in Jan 2016
- 5 wafers, p-type, 230 μm double-sided, non-fully-passing-through columns (a la IBL)
- **First time small pixel size 25x100+ 50x50 μm²** (folded into FEI4 and FEI3 geometries)
  - Also strips and diodes down to 25x25 μm²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

Number of 3D electrodes/pixel

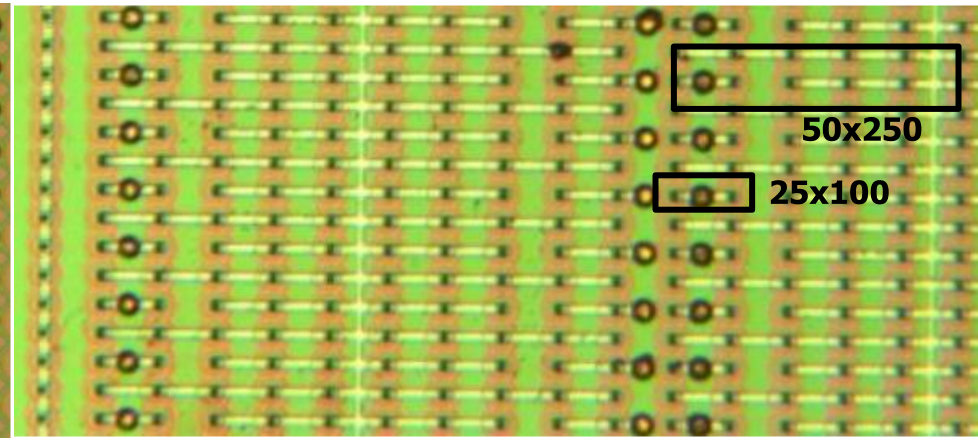
- A: 25x250 μm² 2E - standard FE-I4
- B: 25x500 μm² 5E – i.e. 5x "25x100" 1E, with 3DGR
- C: 50x50 μm² 1E with the rest connected to GND with 3DGR
- D: 25x100 μm² 2E with the rest connected to GND
- E: 50x50 μm² with the rest connected to GND without 3DGR
- F : FEI3 device: 50x50 μm² with rest to GND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

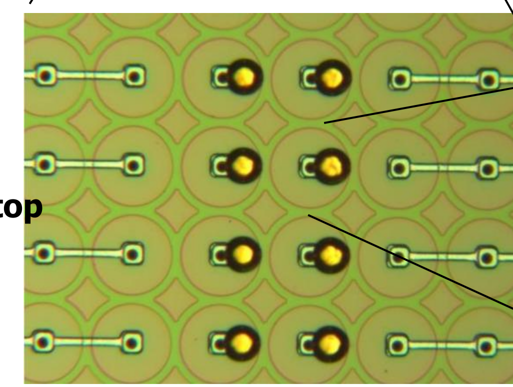
C/E: 50x50 µm² 1E
with the rest connected to GND



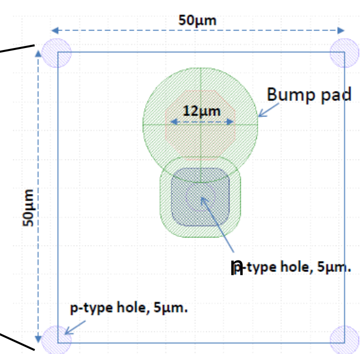
D: 25x100 µm² 2E
with the rest connected to GND



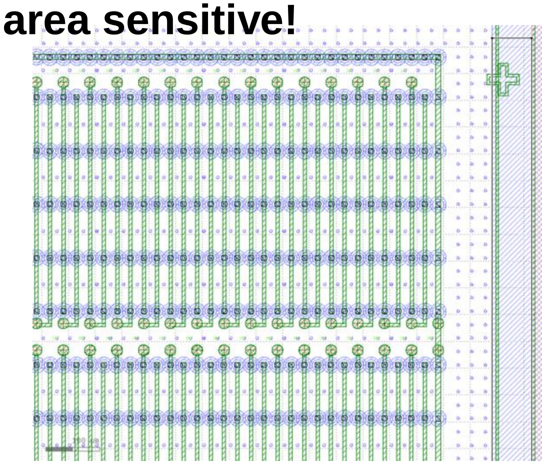
P-stop



Electroless UBM

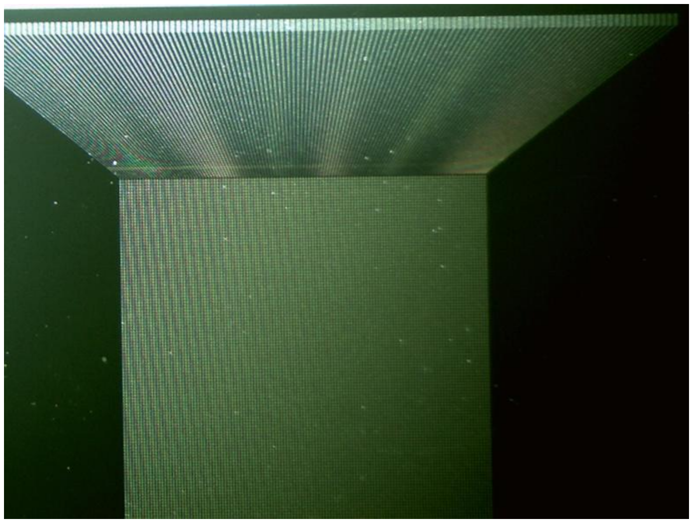


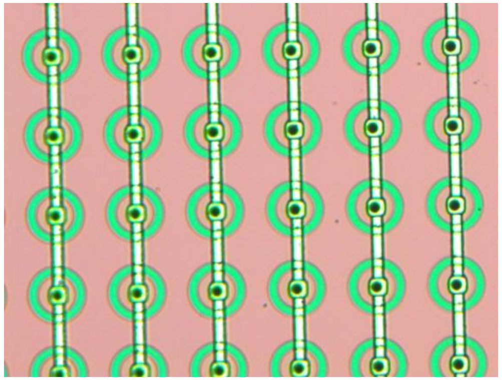
B: 25x500 µm² 5E (= 25x100 1E)
full area sensitive!



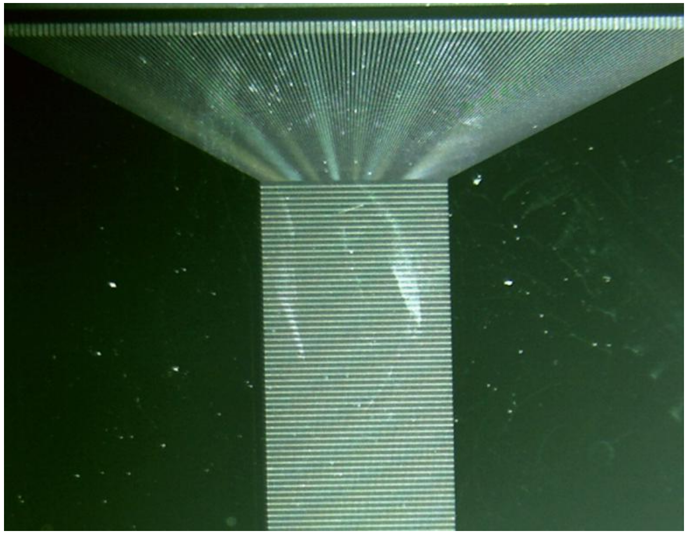
Strips

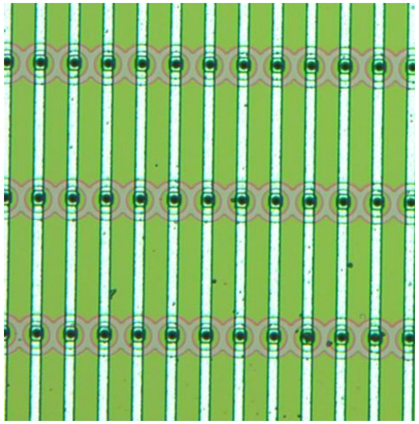
50x50 μm² 3D unit cell
128 strips, 150 3D columns each



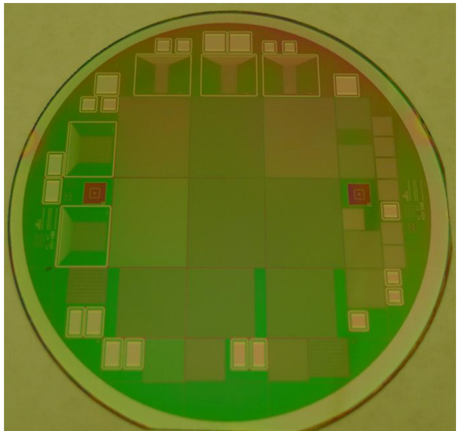


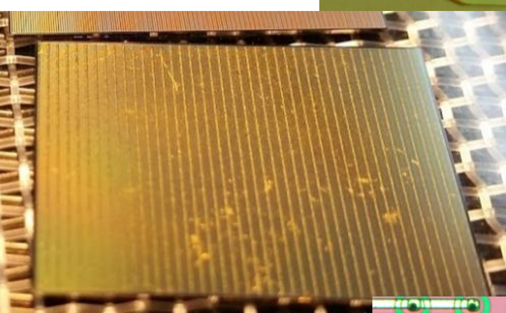
25x100 μm² 3D unit cell
128 strips, 75 3D columns each

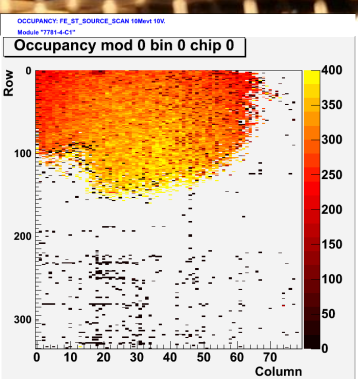


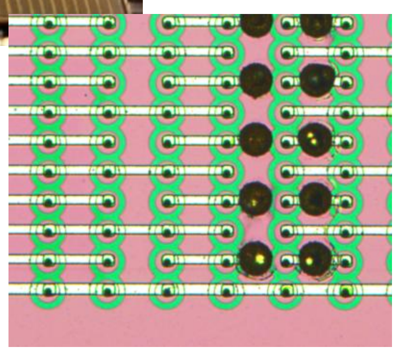


Wafer and Device Status





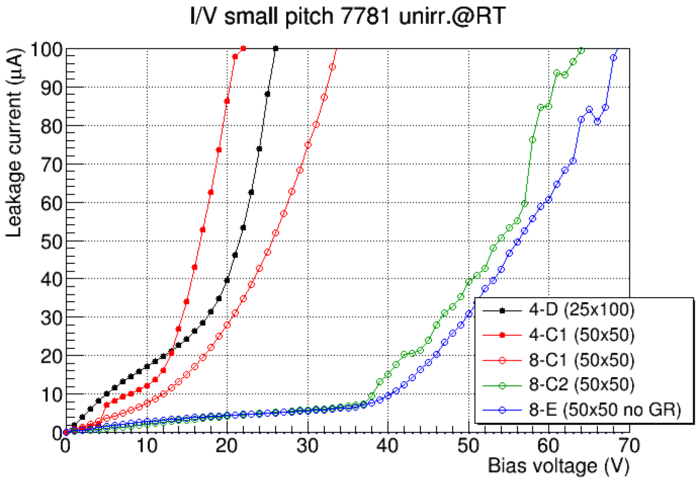


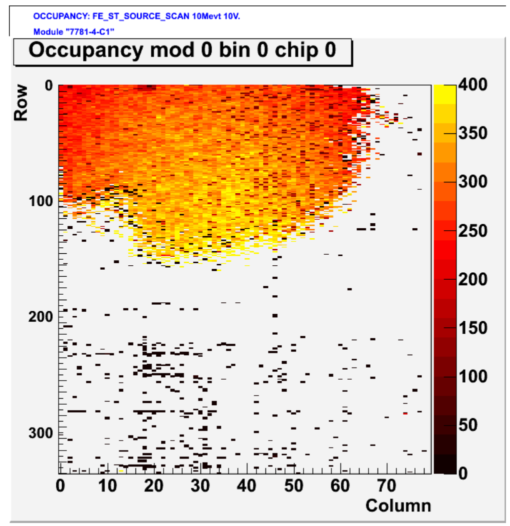


- 5 wafers finished
  - W7: broke - 3 strips recovered, FEI4s broken
  - W4: electro-less Au UBM at CNM on FEI4
  - W8, W3, W5: electro-plate Cu UBM at CNM on FEI4
    - W8 finished
    - W3 and W5 broke during UBM -> try to recover devices
- Pixels
  - FEI4s flip-chipped, assembled and tested at IFAE (4 50x50, 1 25x100)
  - Many disconnected bumps, 2 sensors detached from chip (UBM at CNM not yet optimised)
  - Characterisation and beam tests performed, irradiation on-going
- Strips and Pad Diodes
  - n-irradiation at JSI (5e15+1e16), 2e16 in prep.
  - IV and TCT

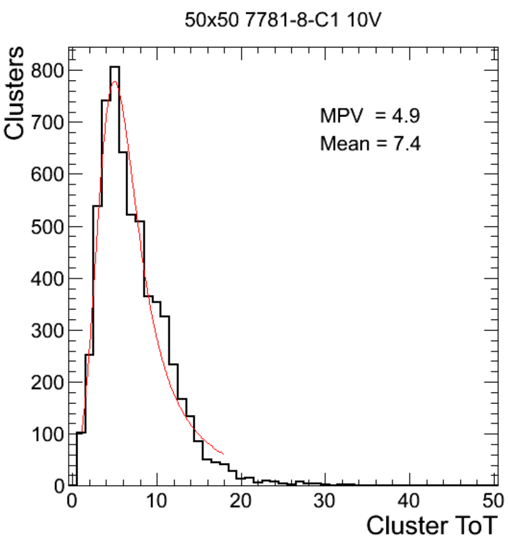
FE-I4 Pixel Characterisations

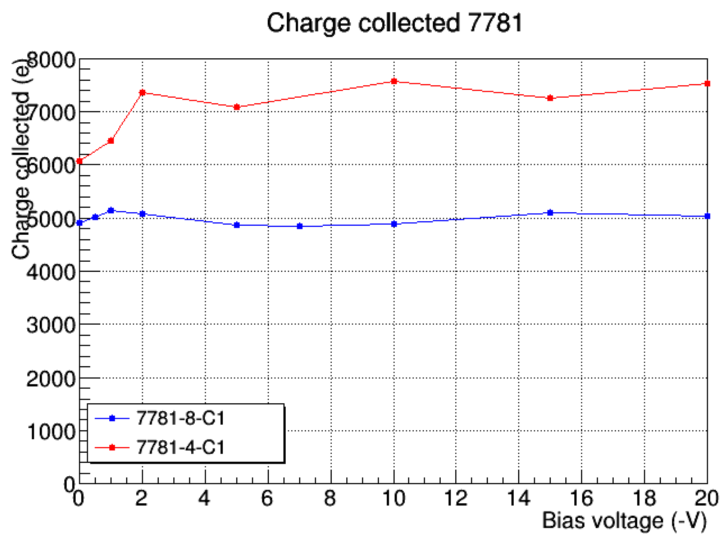
Measurements by D. Vazquez

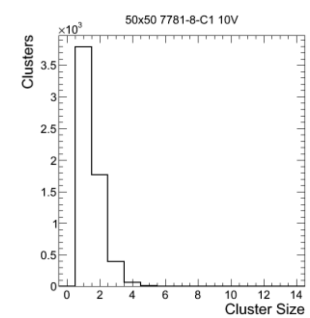




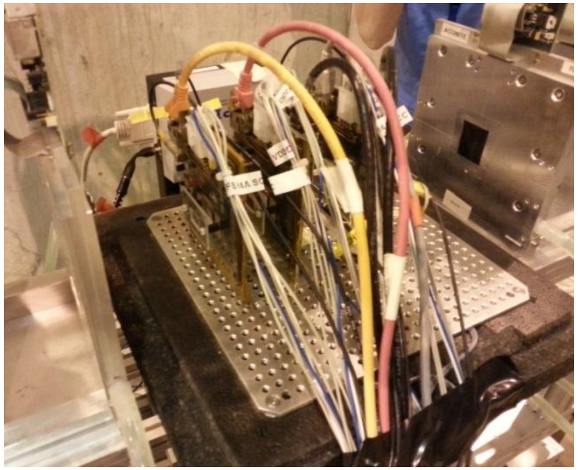
- IVs
  - Breakdown typically 10-40 V (produced before CNM process optimisation)
- Tuning to 2ke threshold and ToT of 10BXs@20ke successful
- Sr90 source scans
  - Devices work apart from disconnected bumps
  - Less charge collected than deposited due to special structure: only 20% fraction of 50x50 pixels connected to FE-I4 bump, rest on GND without recording signal -> charge loss due to charge sharing to non-readout pixels







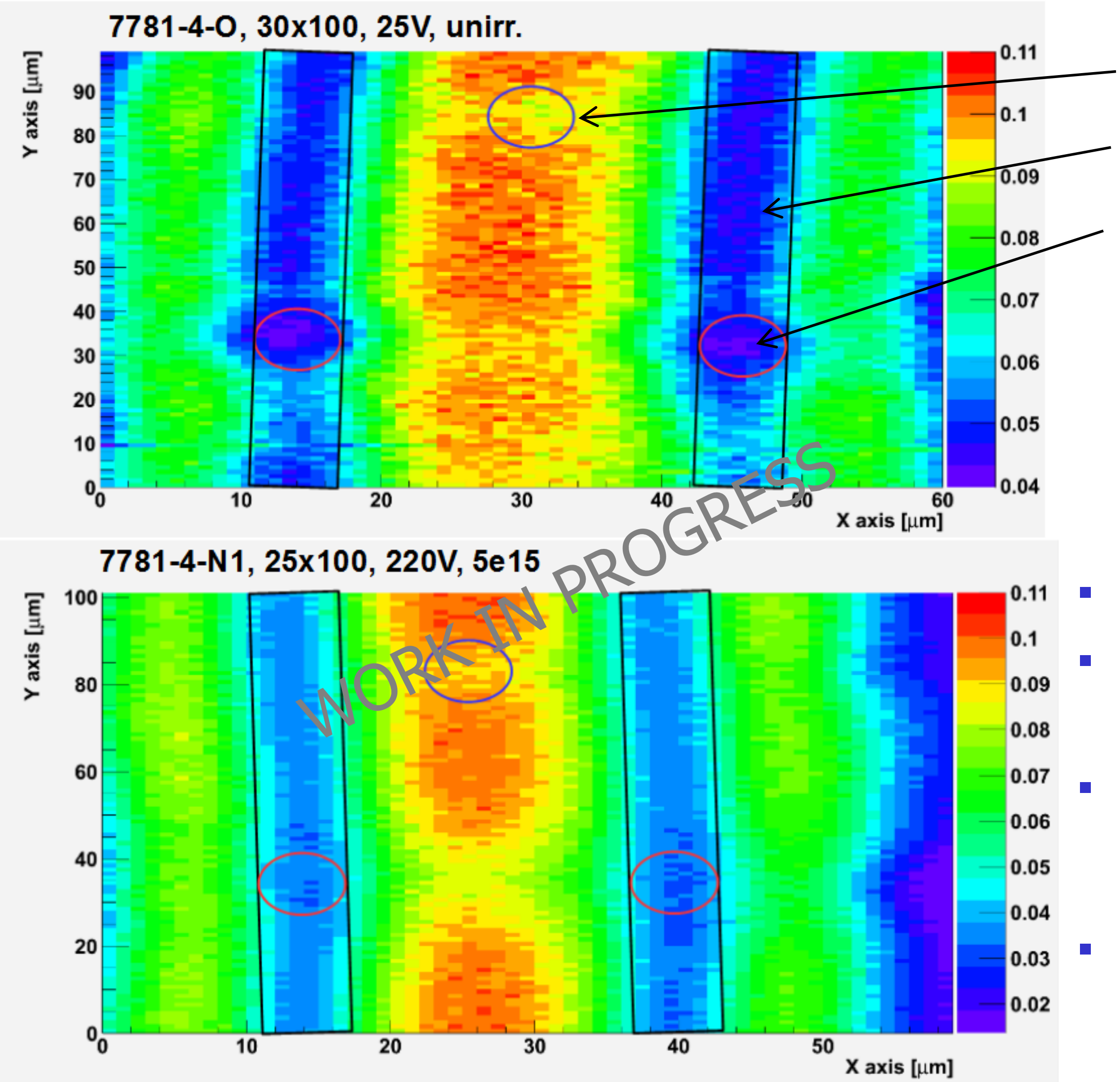
Beam Tests and Irradiations



- 4 FEI4 devices measured in beam tests in May+June 2016 (4 C/E 50x50, 1 D 25x100)
  - Both in AIDA-type telescope and FEI4 telescope
  - Data reconstruction and analysis on-going
- 3 FEI4 Devices being irradiated at PS IRRAD
  - Same devices as in beam test (2 C 50x50, 1 D 25x100)
  - Target fluence: 1e16 n_{eq}/cm^2 over 20x20 mm^2 → peak of 1.4e16 n_{eq}/cm^2
  - Plan to measure in Summer/Fall beam tests
- Irradiation at JSI Ljubljana
  - Strips already irradiated to 5e15+1e16 n_{eq}/cm^2
  - Up to 2e16 n_{eq}/cm^2 for strips, pads +FEI3 soon

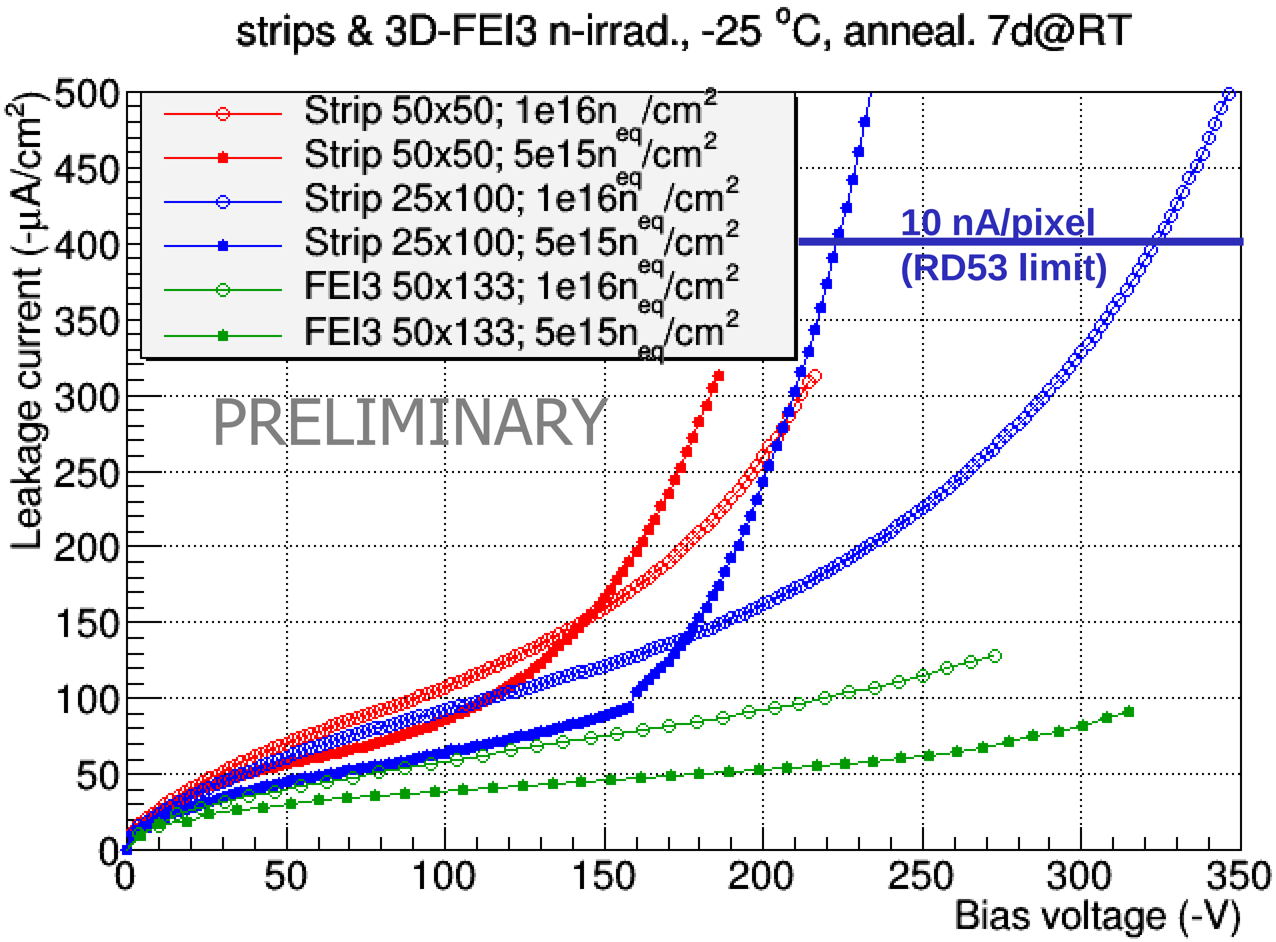
TCT on Strip

Measurements by M. Granado, L. Simon



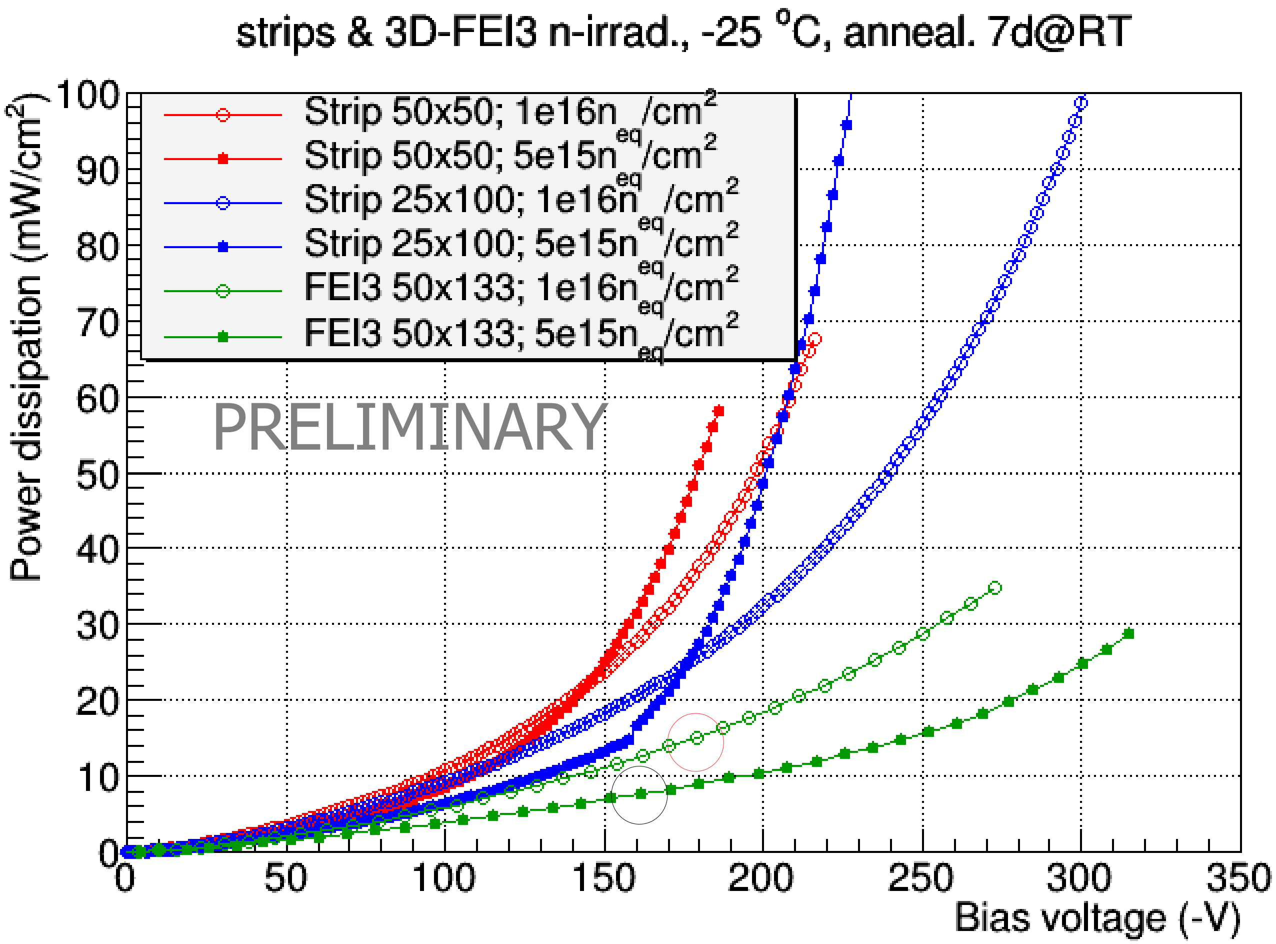
- Surface scan with 1060 nm IR laser
- 2 readout strips (here: summed Q)
  - Normalised to beam monitor
- Still working on TCT optimisation and charge uncertainty determination, measurements and analysis on-going
- **Successful, relatively uniform charge collection even after 5e15 n_{eq}/cm^2**

IV after Irradiation for Different 3D Geometries



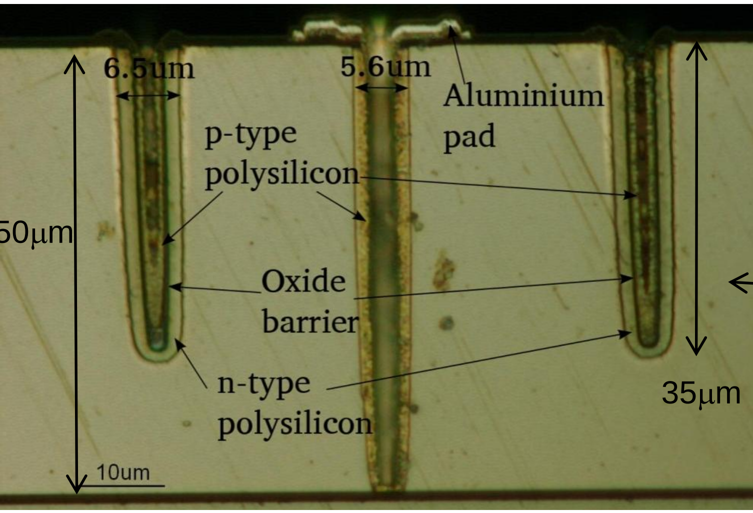
- **Higher I_{leak} and lower V_{BD} for smaller 3D cell sizes**
- Still under investigation
  - Artifact of this run? (before CNM process optimis.)
  - Or real trend for smaller 3D cell sizes due to higher el. field and multiplication?
- Still much lower than RD53 limit of 10 nA/pixel
- **In any case V_{op} will be lower for smaller 3D cell sizes**
  → compensating effect for power

Power after Irradiation for Different 3D Geometries

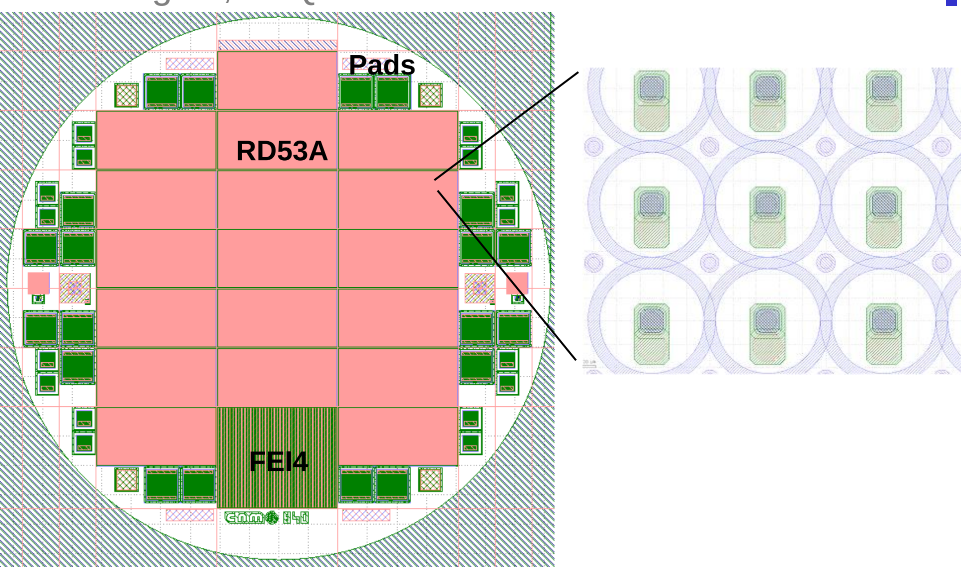


- **V_{op} will be lower for smaller 3D cell sizes**
  → compensating effect for power
- For the same power dissipation as for FEI3 at 1e16 n_{eq}/cm^2 and 180 V (15 mW/cm²), the 50x50 structures need to be operated at 120 V
  → to be studied in a test beam

Up-coming 3D Runs at CNM



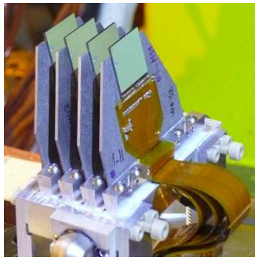
G. Pellegrini, D. Quirion



- New run as copy of 7781 with improved process
  - Expect better yield and IVs (shown by AFP+CT-PPS runs)
  - Production started → expected for end of year
- Thin 3D runs (100-150 µm on SOI)
  - 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 50x50µm² 1E
    - 2 RD53A 25x100µm² 1E
    - 2 RD53A 25x100µm² 2E
    - 1 FEI4 50x50µm² 1E (equivalent to 7781 C)
    - Pad diodes of 50x50µm² and 25x100µm² (big and small)

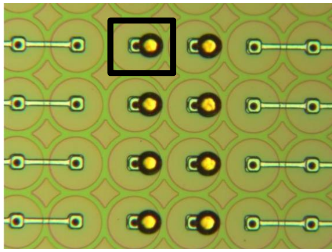
Conclusions

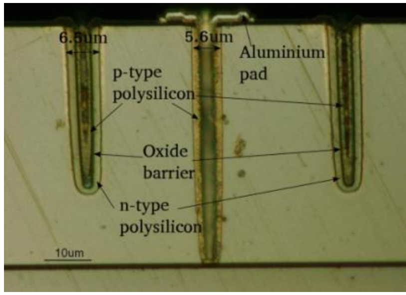
- AFP 3D FEI4 modules assembled by IFAE, installed and taking LHC data
  - Preparing for second-phase production and installation in EYETS 2016/17 (16 modules)
  - Huge sensor yield improvement to 94% for second AFP sensor production at CNM



- Studied IBL-type 3D pixel detectors up to HL-LHC fluences
  - 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
  - Measurements with devices up to 2.2e16 n_{eq}/cm^2 performed (analysis on-going)
- First new-generation 3D production with small ITk pixel size
  - Characterisation and beam tests of FEI4s performed, irradiation on-going
  - Irradiation of strips with n up to 1e16 n_{eq}/cm^2
    → higher I_{leak} than for IBL-type still under investigation, but will need less V_{op}
- Single-sided thin 3D and RD53-chip geometry under way
  - 72, 100 + 150 µm SOI

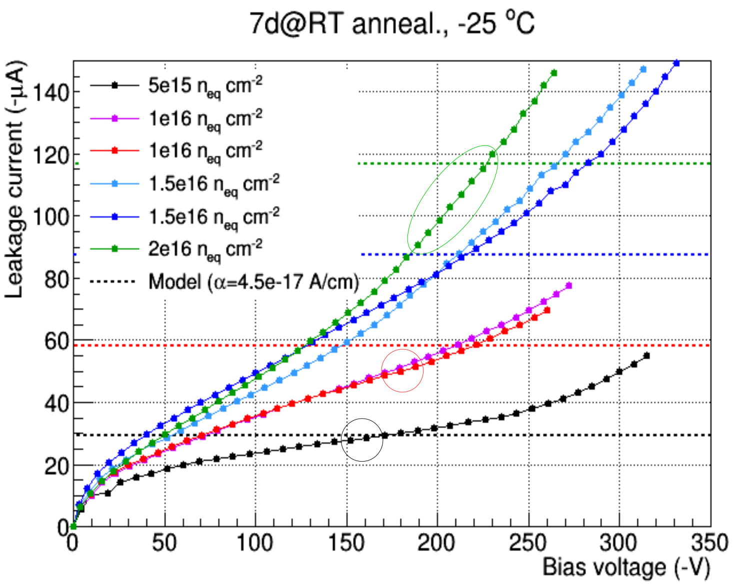
50x50 µm²





BACKUP

n-Irradiated IBL-Type FEI3



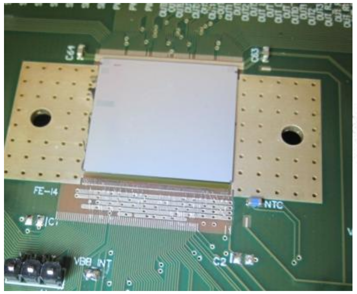
- Uniformly n-irradiated FEI3 (JSI) → I_{leak} measurements
  - Fluence dependence roughly as expected → dominated by radiation-induced bulk current
  - **Power dissipation 15 mW/cm² at 1e16 n_{eq}/cm²** at V_{op}=180 V for IBL-type geometry (L=71 µm, 230 µm thickness)

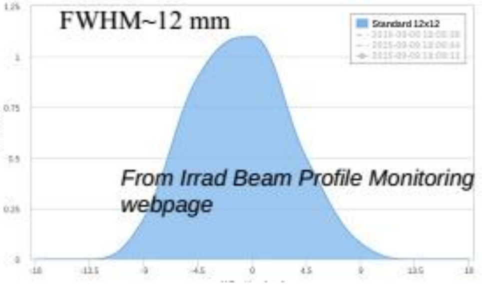
D. Vazquez (ITk Week Sep 2015)

Irradiation of IBL 3D Pixels

- PS IRRAD 23 GeV p (Nov 2014 + Fall 2015)

Thanks to Federico Ravotti for irradiation!



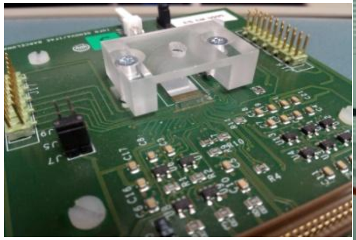


  - FEI4 3D pixel detectors
  - Non-uniform (12 mm FWHM beam)
    → difficult for IV/power dissipation studies
  - In 2014 reached 9e15 n_{eq}/cm^2
    - Assembled at IFAE + measured in ITk beam tests
  - End 2015 further irradiation to 2.2e16 n_{eq}/cm^2 finished
    - To be assembled at CERN for May 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

- JSI Ljubljana n (May 2015)

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

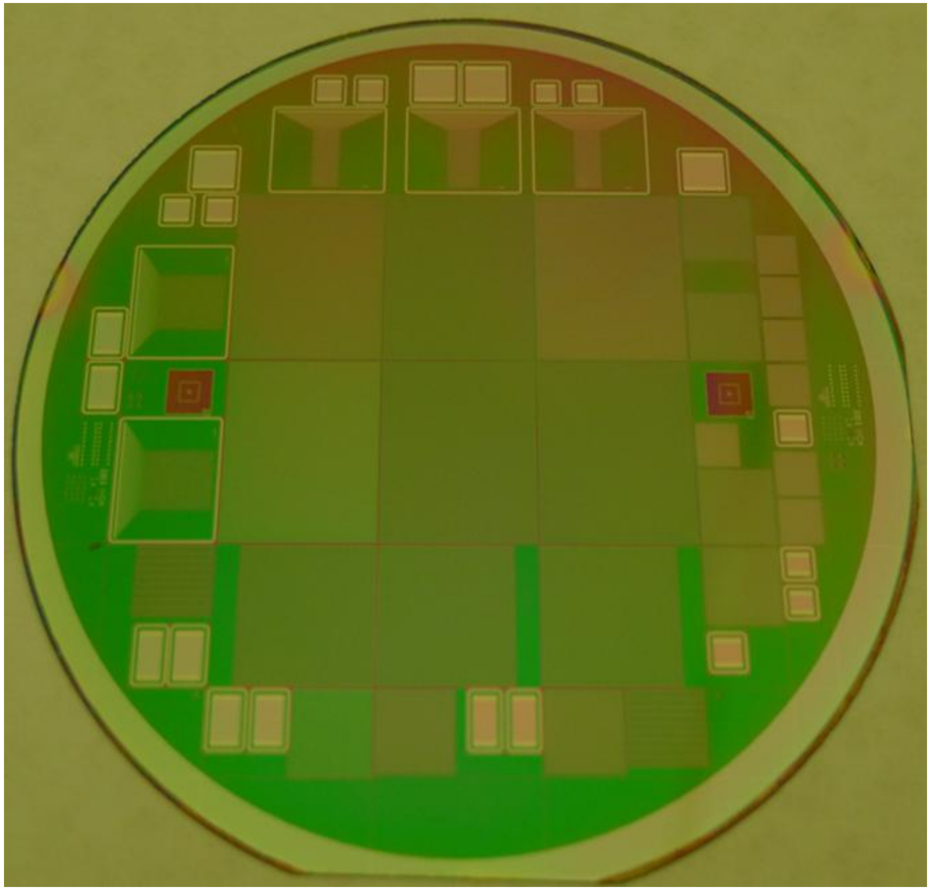


  - FEI4 has problem of Ta activation
    → take FEI3
  - Also have plenty FEI3s from CNM IBL wafers with great V_{BD}>100 V
  - Uniform irradiation good for IV/power dissipation study
  - Fluences:
    5e15, 1e16 (2x), 1.5e16 (2x), 2e16 n_{eq}/cm^2
  - Assembled at IFAE (bump- and wire-bond + gluing)

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**

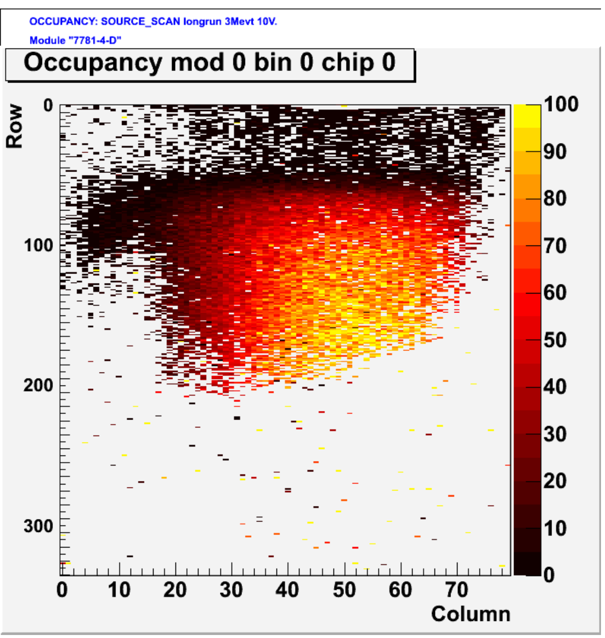
→ Increased aspect ratio 26:1 (nom.)

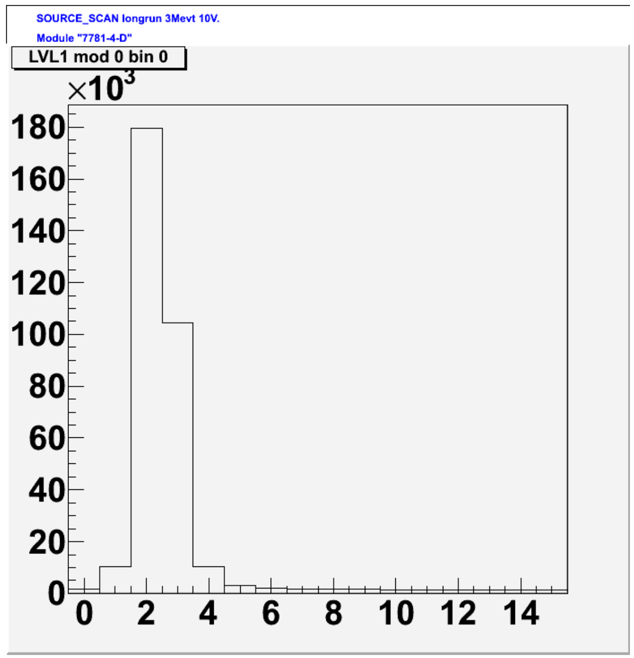
FE-I4s – 7781-4-D (25x100 2E)

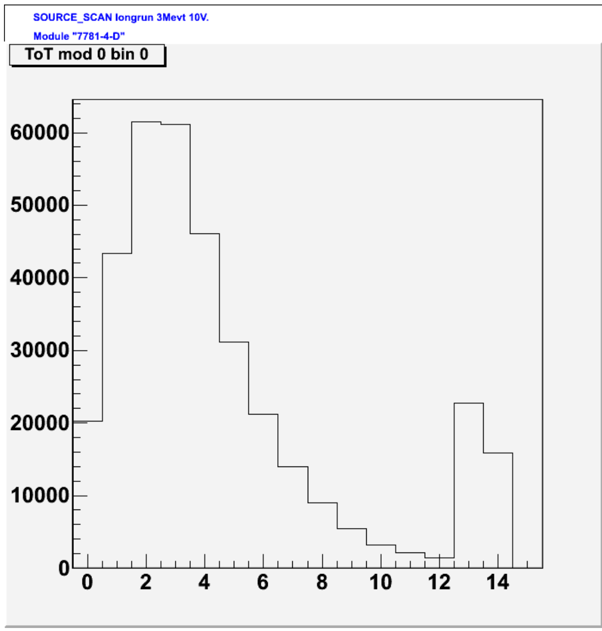
Measurements by D. Vazquez

- Electroless UBM on first wafer at CNM
  - Poor UBM: Large regions of disconnected bumps
  - But small connected region
- Tuning to 2ke and 10@20ke and source scans successful -> device works
  - Note special structure (only 20% fraction of 50x50 pixels connected to FE-I4 bump, rest on GND without recording signal)

C1: 50x50 µm², 5V

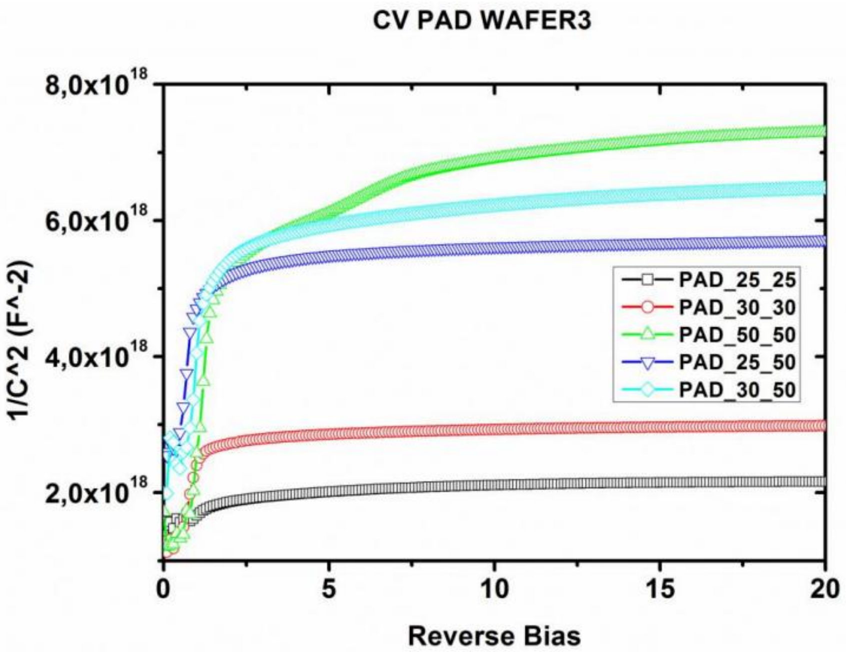




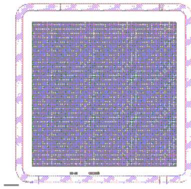


Capacitance

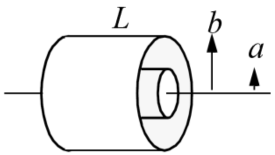
Measurements by M. Carulla



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):

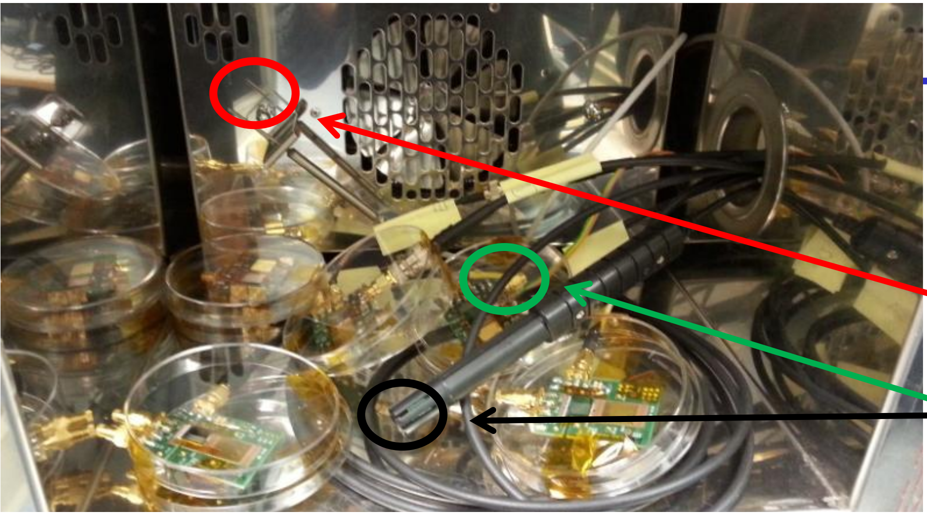


$$C = \frac{2\pi\varepsilon_0 L}{\ln\left(\frac{b}{a}\right)}$$

- 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

Leakage Current of Irradiated Strips



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

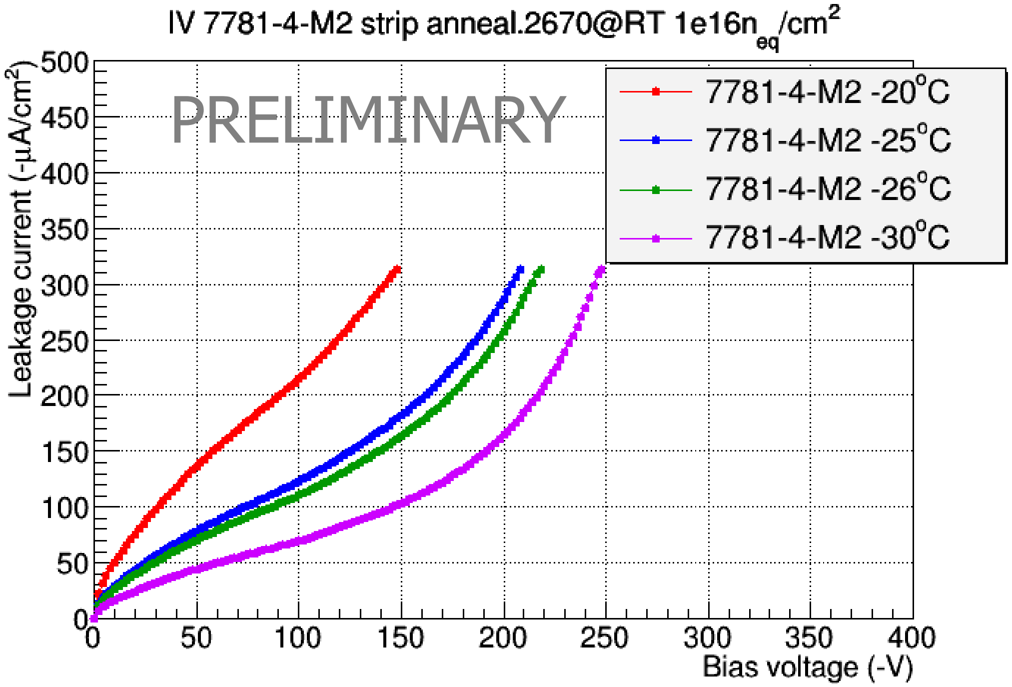
- IFAE climate chamber on TCT PCBs
- Standard: set to -25°C
- T monitoring
  - Climate chamber internal: -25°C
  - T meter near door: -23.8°C
  - Pt100 on sensor M2: -24.2°C

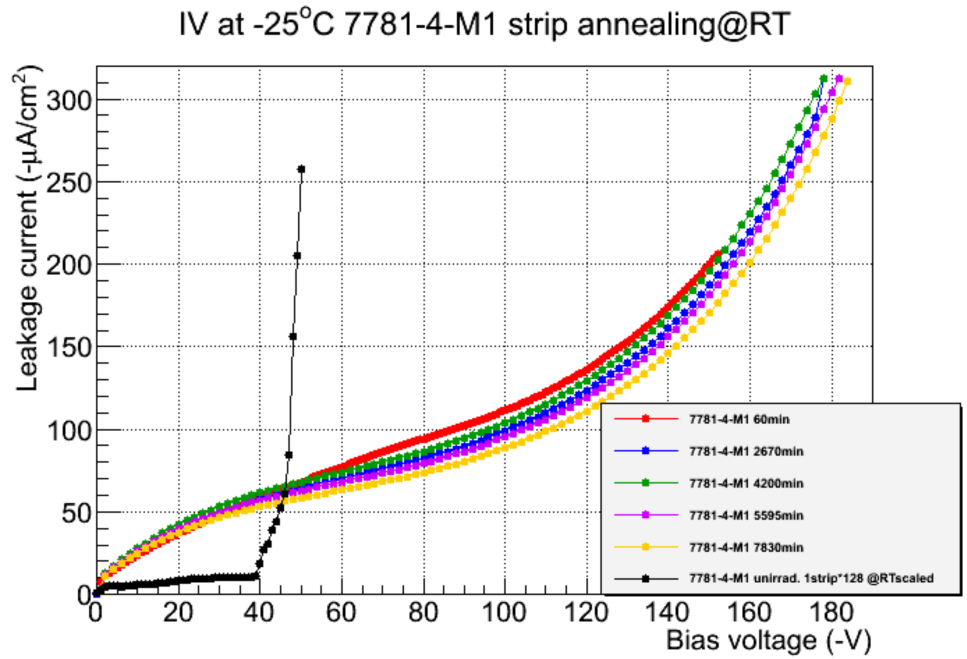
→ variation up to 1.2°C

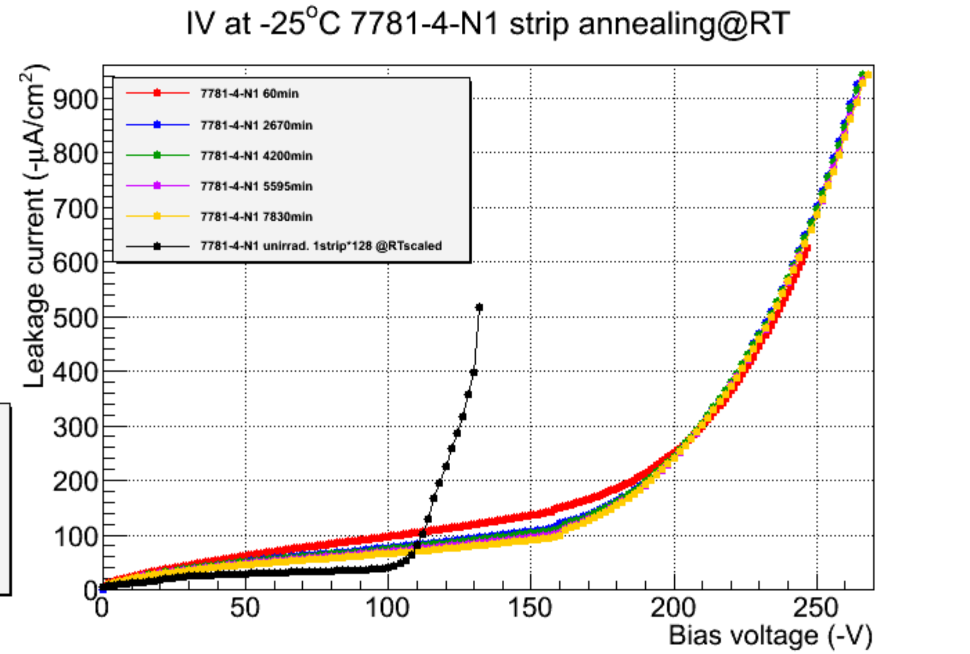
→ 10% difference in leakage current

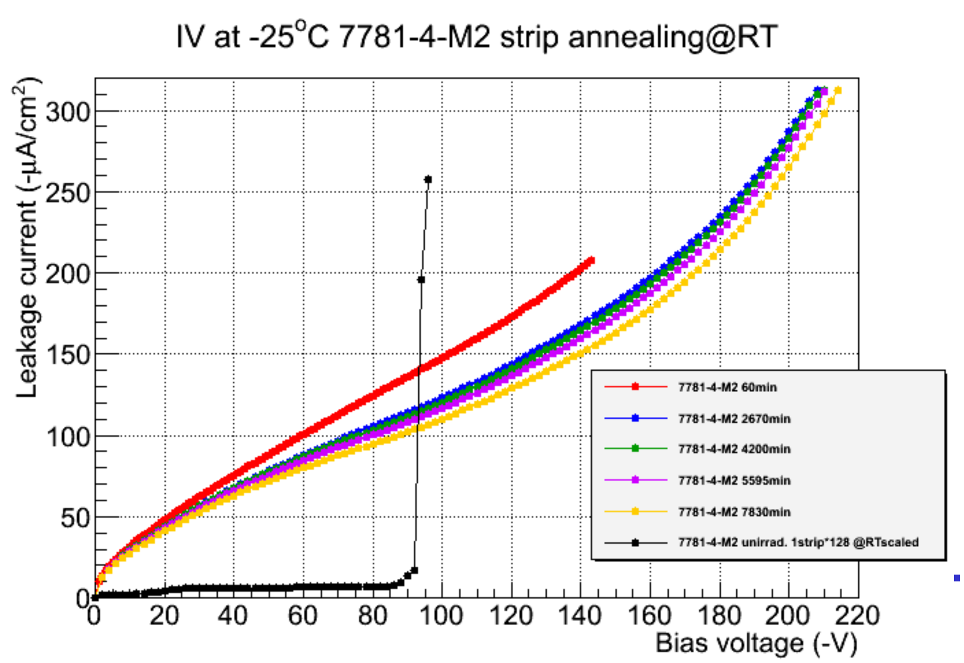
→ values presented here are upper limits for -25°C

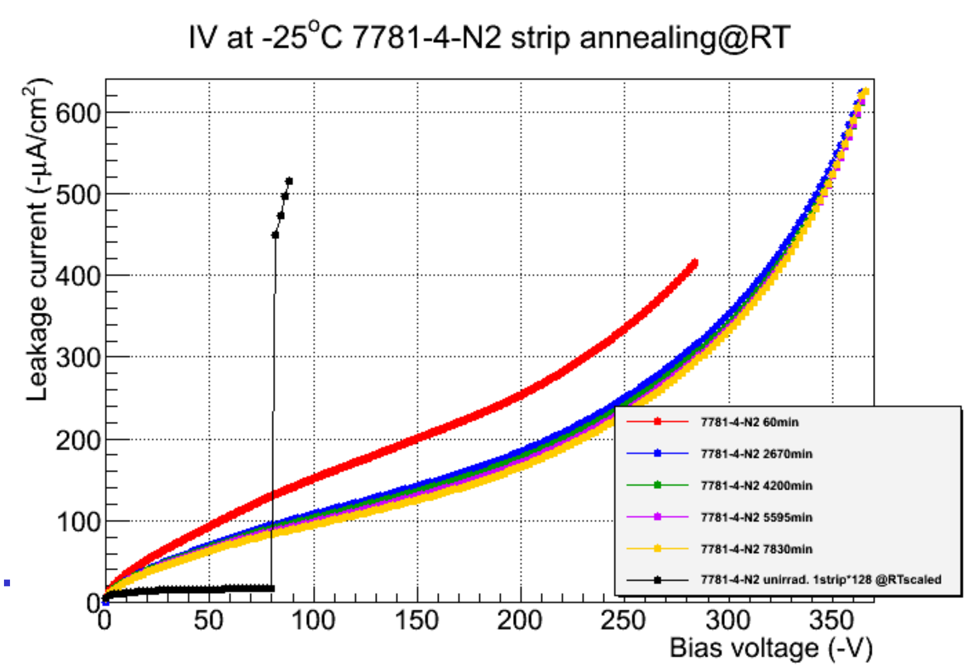
- Self-heating during IV (1s/point) max. 0.2°C
- Annealing study up to 7d@RT (22-25°C)




IV at -25°C 7781-4-M1 strip annealing@RT
Leakage current (-µA/cm²)
Bias voltage (-V)
7781-4-M1 60min
7781-4-M1 2670min
7781-4-M1 4200min
7781-4-M1 5595min
7781-4-M1 7830min
7781-4-M1 unirrad. 1strip*128 @RTscaled


IV at -25°C 7781-4-N1 strip annealing@RT
Leakage current (-µA/cm²)
Bias voltage (-V)
7781-4-N1 60min
7781-4-N1 2670min
7781-4-N1 4200min
7781-4-N1 5595min
7781-4-N1 7830min
7781-4-N1 unirrad. 1strip*128 @RTscaled


IV at -25°C 7781-4-M2 strip annealing@RT
Leakage current (-µA/cm²)
Bias voltage (-V)
7781-4-M2 60min
7781-4-M2 2670min
7781-4-M2 4200min
7781-4-M2 5595min
7781-4-M2 7830min
7781-4-M2 unirrad. 1strip*128 @RTscaled


IV at -25°C 7781-4-N2 strip annealing@RT
Leakage current (-µA/cm²)
Bias voltage (-V)
7781-4-N2 60min
7781-4-N2 2670min
7781-4-N2 4200min
7781-4-N2 5595min
7781-4-N2 7830min
7781-4-N2 unirrad. 1strip*128 @RTscaled

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)

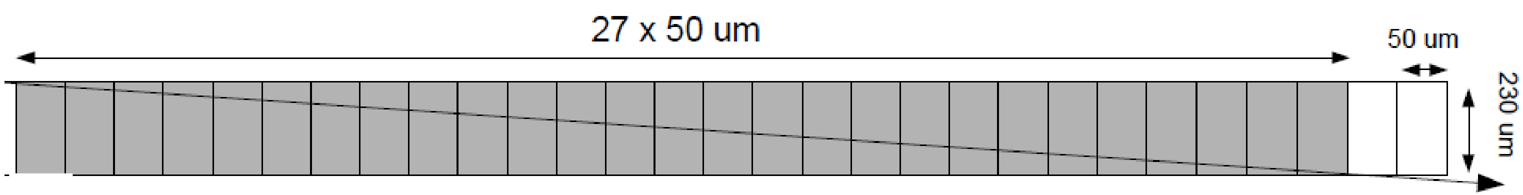
[1] Measured by IFAE 2015 at -25˚C, 7d@RT annealing (this talk)
[2] ATLAS IBL Coll., JINST 7 (2012) P11010, remeasured by IFAE 2015 at -25˚C, 120min@60C annealing
[3] C. Fleta, RD50 Workshop June 2010, measured at -10˚C, 1d@RT or 4min@80˚C annealing
[4] M. Köhler, PhD thesis Uni Freiburg, 2011, presented 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

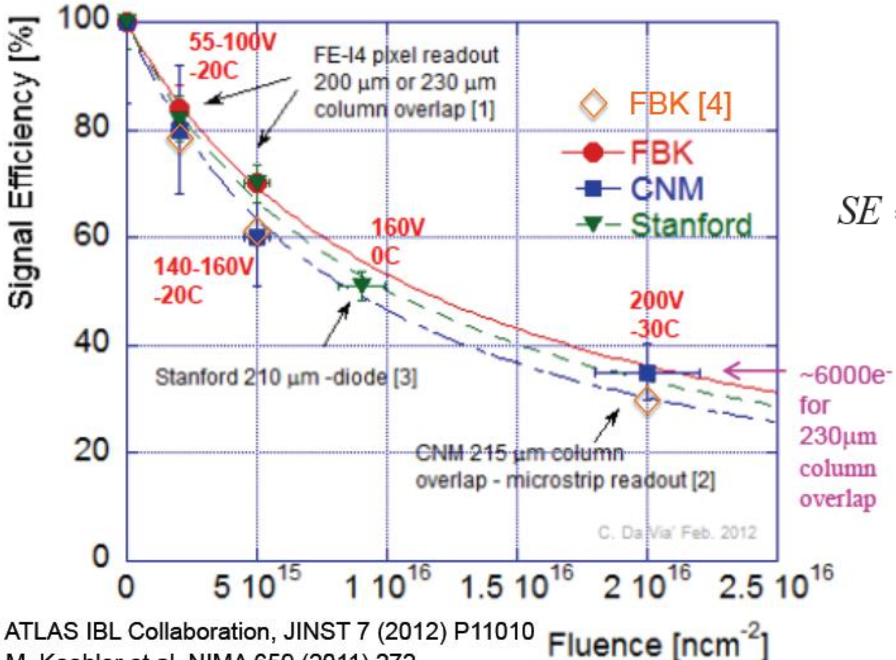
- Large clusters → large total charge → efficiency for whole cluster not a problem
- But for 50 µm pitch very small charge deposition per pixel (almost parallel tracks): 3300 e
- Testbeam campaign to measure CNM+FBK IBL FE-I4 devices with 80° angle in short pitch direction (50 µm)
  - 1000 + 1500 e threshold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

See talk by Ivan Lopez, RD50 Workshop June 2015

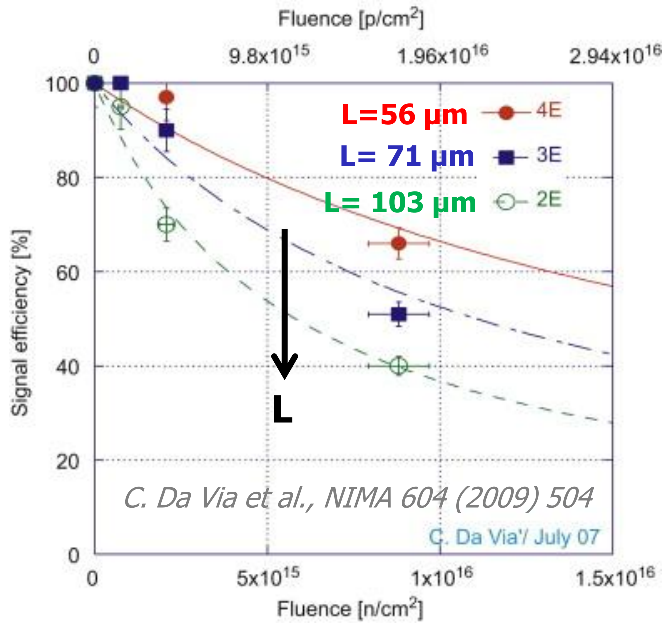
80° (η=2.4) → Q=3300 e/pixel (50 µm)



R&D Performance Summary

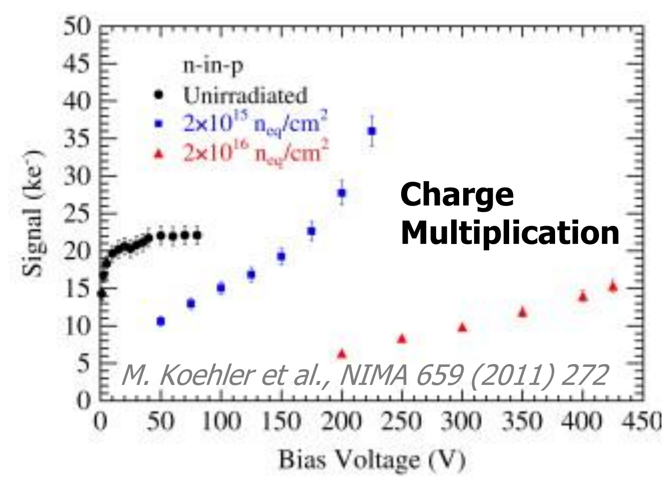


$$SE = \frac{1}{1 + 0.6L\frac{K_\tau}{v_D}\Phi}$$



[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 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