Radiation hardness of 3D pixel detectors up to 2e16 n_{eq}/cm^2

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IFAE Barcelona

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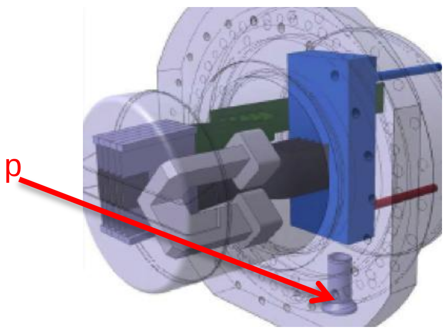
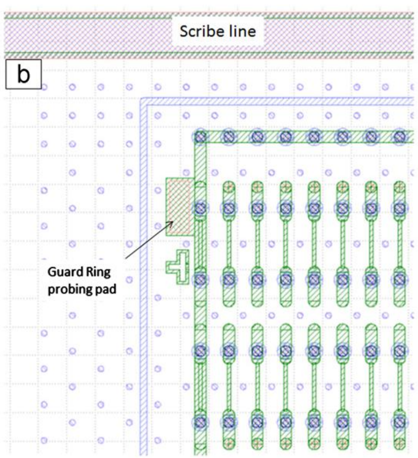
Today's 3D Pixel Detectors

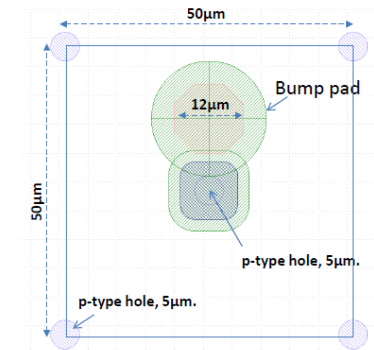




- ATLAS IBL
  - 25% 3D detectors
  - Installed and running!
    → 3D in action
- ATLAS Forward Proton (AFP)
  - Successful 3D sensor qualification
  - 3D module production on-going at IFAE
  - To be installed early next year
- Properties of IBL/AFP 3D pixel detectors
  - 230 μm thick sensors by CNM and FBK
  - FEI4s: 50x250 μm, 67 μm inter-el. spacing
  - FEI3s (tests): 50x400 μm, 71 μm inter-el. spacing
  - Radiation hardness up to 5e15 n_{eq}/cm^2 established
    - >97% hit efficiency above 160 V
      (conservative! In fact for many devices already from 120 V)
    - Low power dissipation: 10-15 mW/cm^2 at T=-15 C

New Developments for HL-LHC

- High-Luminosity LHC (HL-LHC) upgrade 2024
  → increased occupancy
  → unprecedented radiation levels (1-2x10^{16} n_{eq}/cm^2 innermost pixels)
- Development of new pixel sensors and front-end (RD53)
  - Reduced pixel size: 50x50 μm^2 or 25x100 μm^2
  - Reduced 3D inter-electrode distance
  - Possibly reduced thickness (100-150 µm)
  - Reduced threshold ~1000e (in-time)
- Strategy for 3D HL-LHC R&D
  - New generation of 3D productions under way
    - But takes time (~1 year)
    - First small-pixel run almost finished now → See Giulio's talk
    - First very thin (50 µm) single-sided CNM run ready → See Giulio's talk
  - Explore the limits of existing 3D technology and devices (IBL/AFP generation)
    - Neutron irradiated FEI3 up to 2e16 n_{eq}/cm^2 → this talk
    - Proton irradiated FEI4 up to ~1e16 n_{eq}/cm^2 → next talk (I. Lopez)
    - Efficiency of 50 µm pitch under high angle → I. Lopez, 26th RD50 Workshop, Santander, 2015



G. Pellegrini, CNM

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

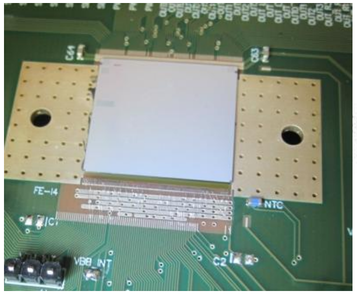
cf. FE-I4: L=67 µm

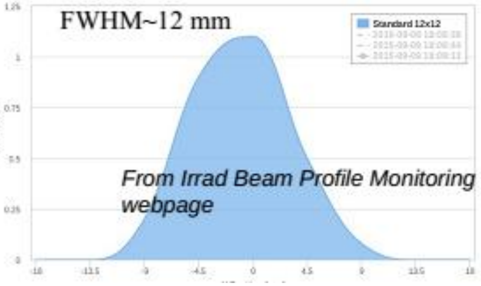
HL-LHC Studies: Irradiation Campaigns

- 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
    - Beam tests successful → see I. Lopez' talk
    - Now further irradiation to 2e16 n_{eq}/cm^2 finished
    - 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

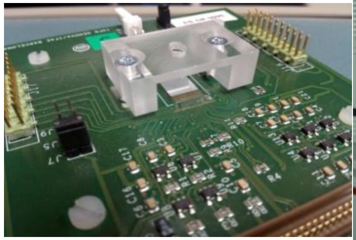
Thanks to Federico Ravotti for irradiation!





- 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} of 300 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!

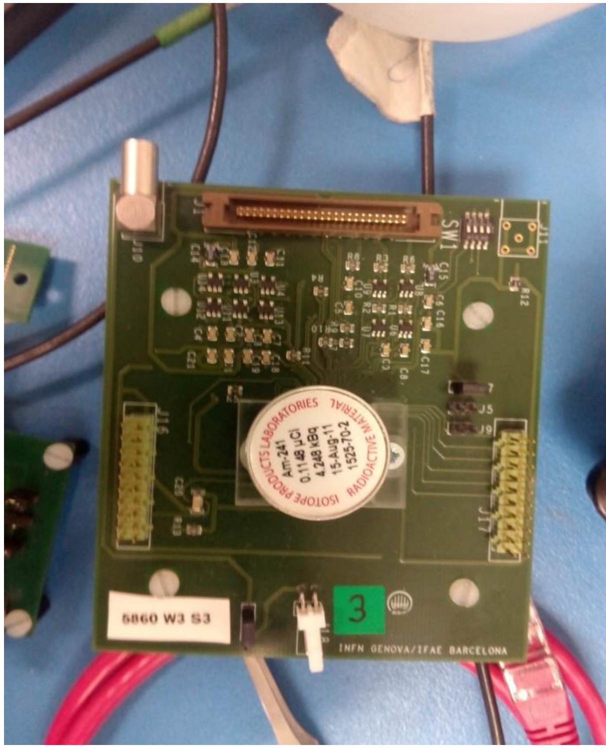


First time 3D pixel detectors irradiated to HL-LHC fluences!

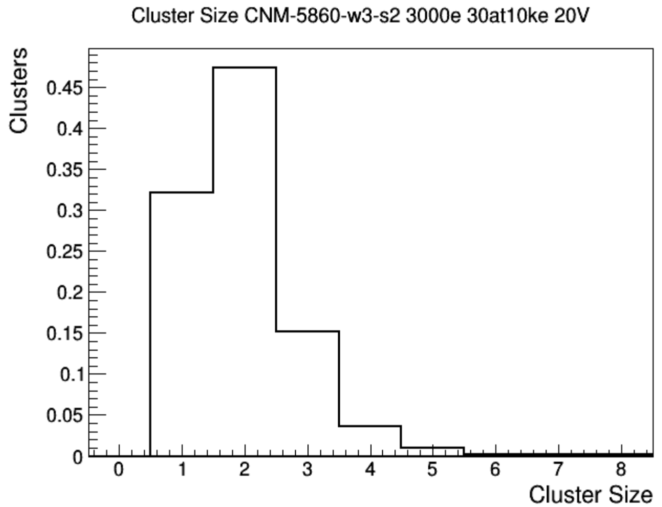
FEI3 Charge Collection Studies

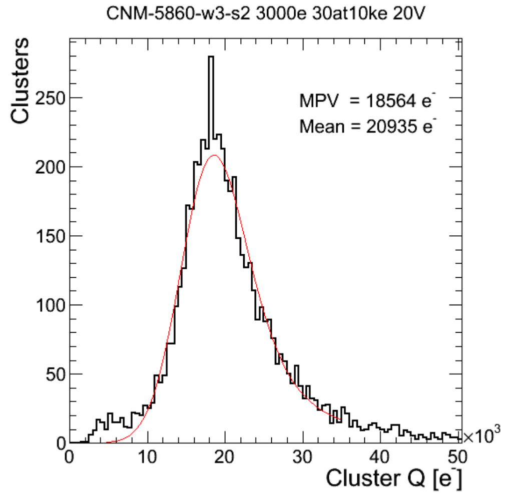
- Sr 90 source (not collimated)
- External scintillator trigger
- USBpix readout system
- Tuning
  - Relatively high threshold of FEI3:
    compared 2.5, 3 and 3.5 ke
  - 30 ToT at 10 ke
  - Performed ToT to Q calibration with FEI3 charge injection circuit
- Measurement temperature
  - Climate chamber set to -30 C
  - On-sensor T~-25 C: benchmark T for ATLAS ITk
    (see slides later)

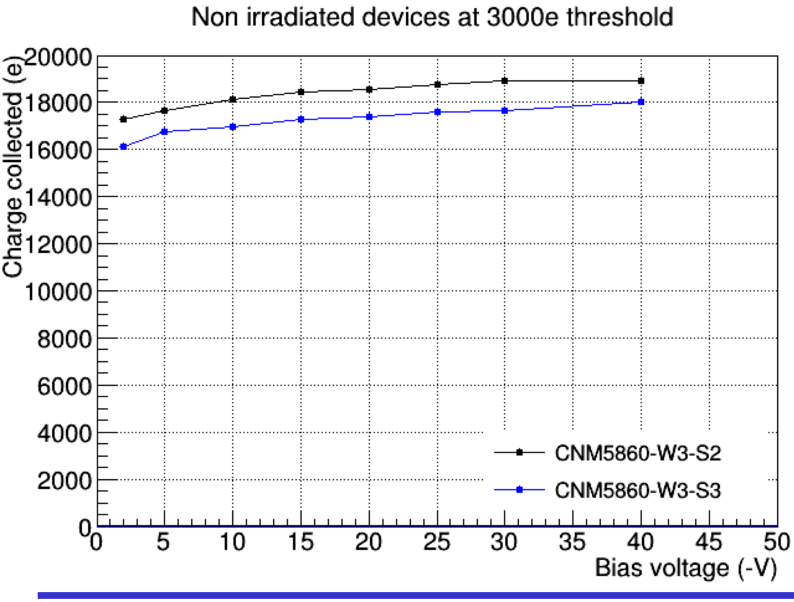
Measurements by D. Vazquez



Charge Collection Studies – Unirradiated

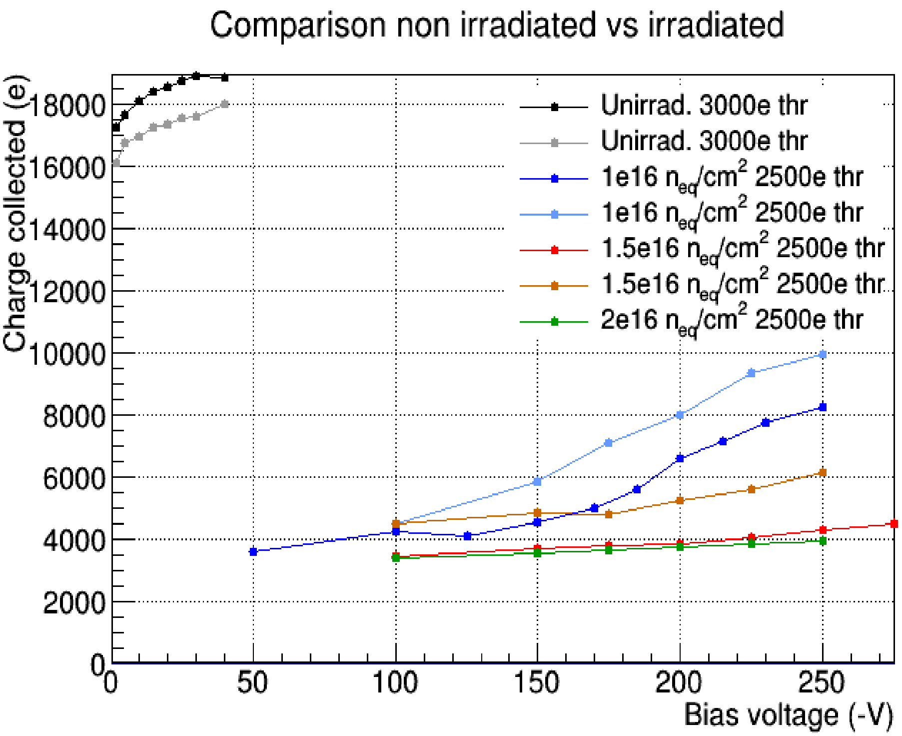


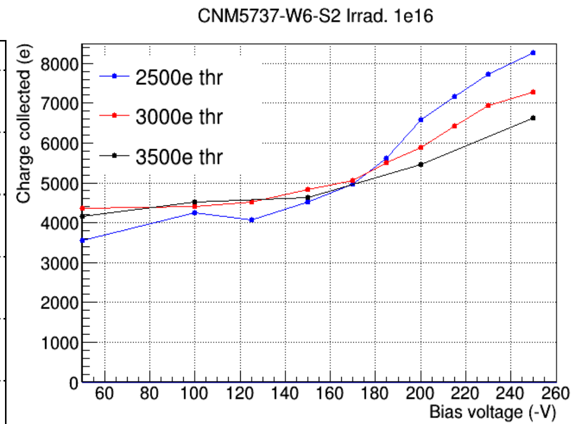


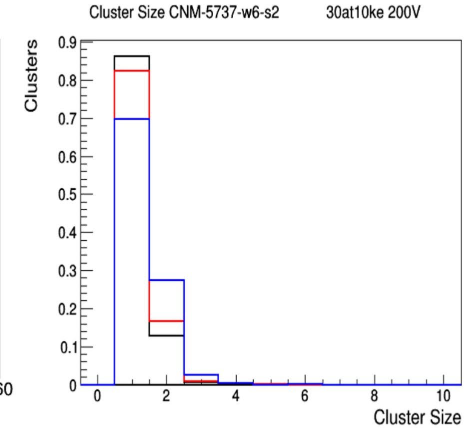


- Cluster size ~2 (not collimated)
- Landau*Gauss shape
- MPV plateau ~18 ke
  - In agreement with expected 17 ke (for 73 e-h pairs/μm and 230 μm)

Charge Collection Studies – Irradiated





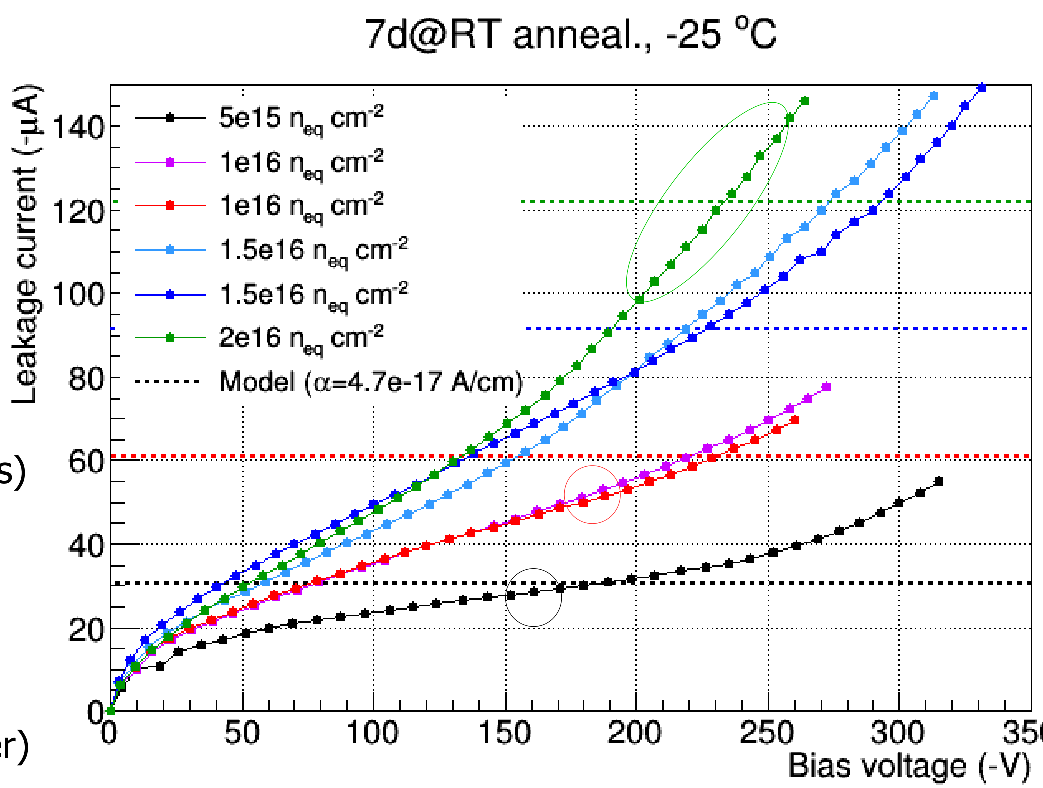


- Threshold dependence: Charge and hit loss at higher thresholds
- Even with FEI3 threshold of 2.5 ke and 71 µm 3D inter-electrode distance: Q~4 ke (for 230 µm) and CCE~21% at 200 V for 2e16 n_{eq}/cm^2!
  - Cf. to strips (no threshold, 57 µm el. dist.): CCE~30-35% at 200 V [4,5]
- Expect improvement for RD53 threshold of 1 ke and 35 µm 3D inter-electrode distance
  - Partly compensated for total charge if going thinner for normal incidence

FEI3 Leakage Current: Fluence Dependence

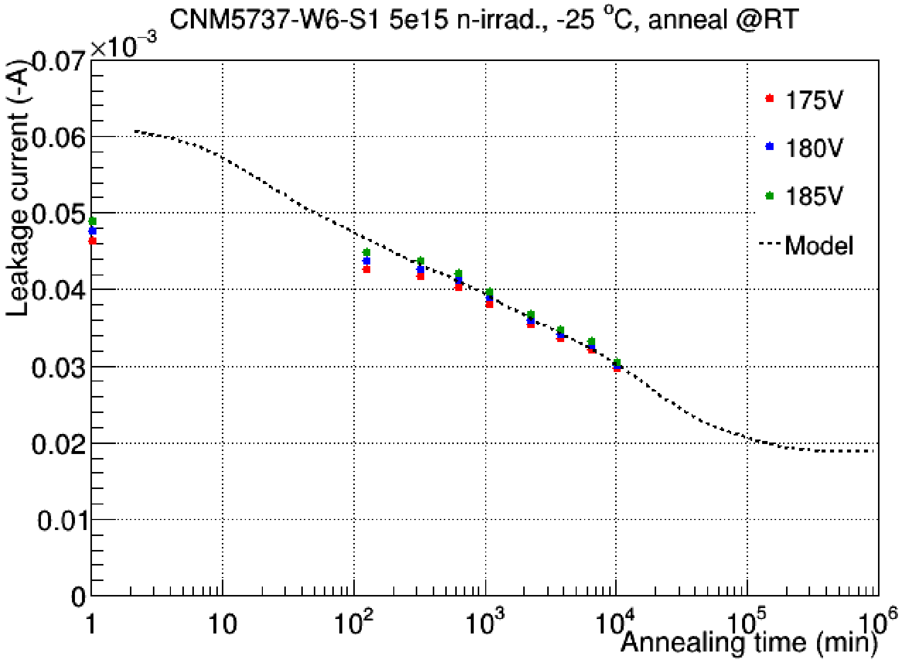
Measurements by D. Vazquez

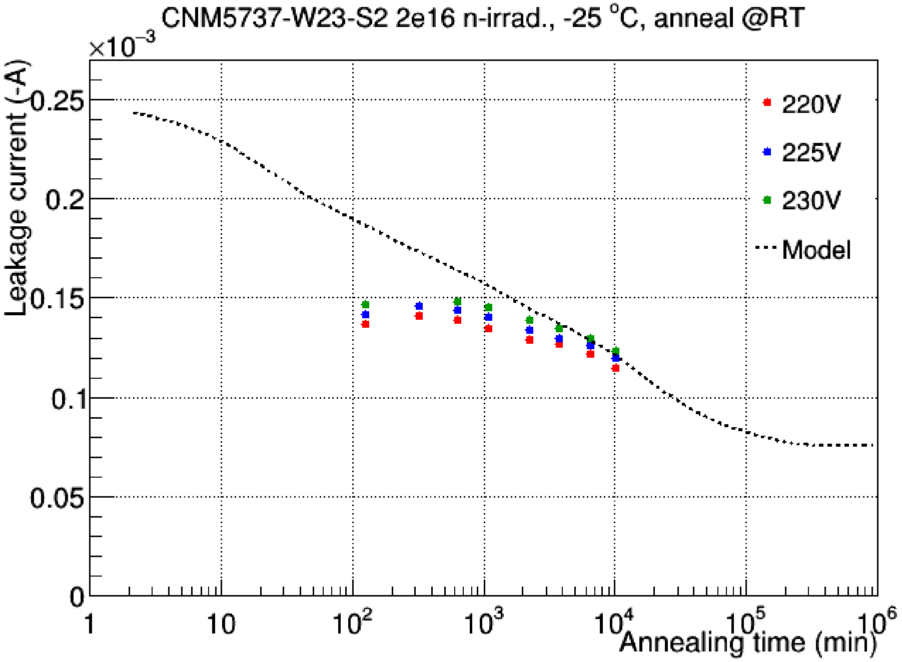
- Climate chamber set to -25 C (chip off)
  - Benchmark T for ATLAS ITk
- Annealing to 7d at room temperature
- Fluence dependence as expected
  - Devices at same fluence agree reasonably
- Definition of operational V_{op}
  - Point where hit efficiency >97%
  - 5e15 n_{eq}/cm^2: 160 V (IBL beam tests)
  - 1e16 n_{eq}/cm^2: 180 V (new FEI4 beam tests) (see I. Lopez' talk)
  - 2e16 n_{eq}/cm^2: 200-250 V
    from charge collection: Q~4 ke, CCE>20%
  - Will need less V_{op} for smaller electrode dist. (but possibly some compensation for thinner)
- Current at V_{op} similar to model prediction with α=4.7e-17 A/cm



Model by Wunstorf/Moll

Leakage Current: Annealing

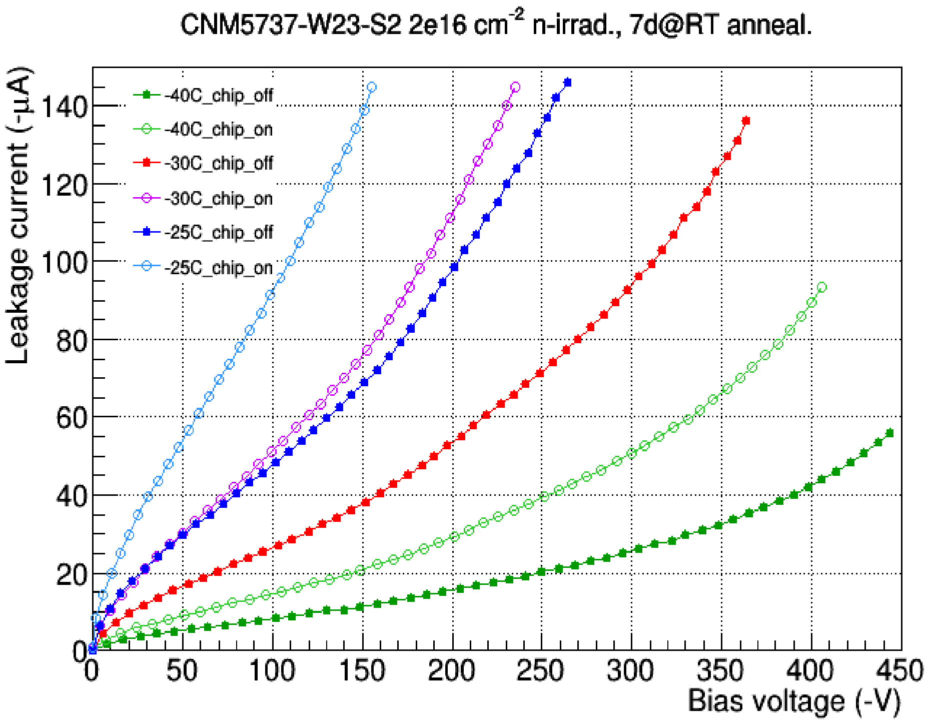


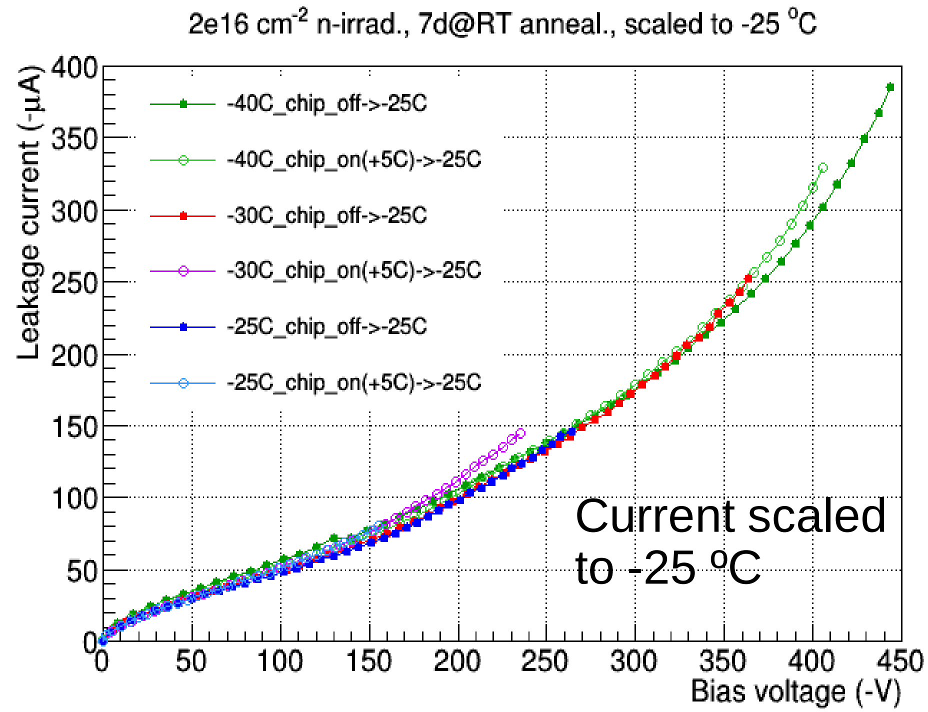


Model by Wunstorf/Moll

- Current decreases with annealing as expected
  - By ~20% after 1 week at room temperature

Leakage Current: Temperature Dependence



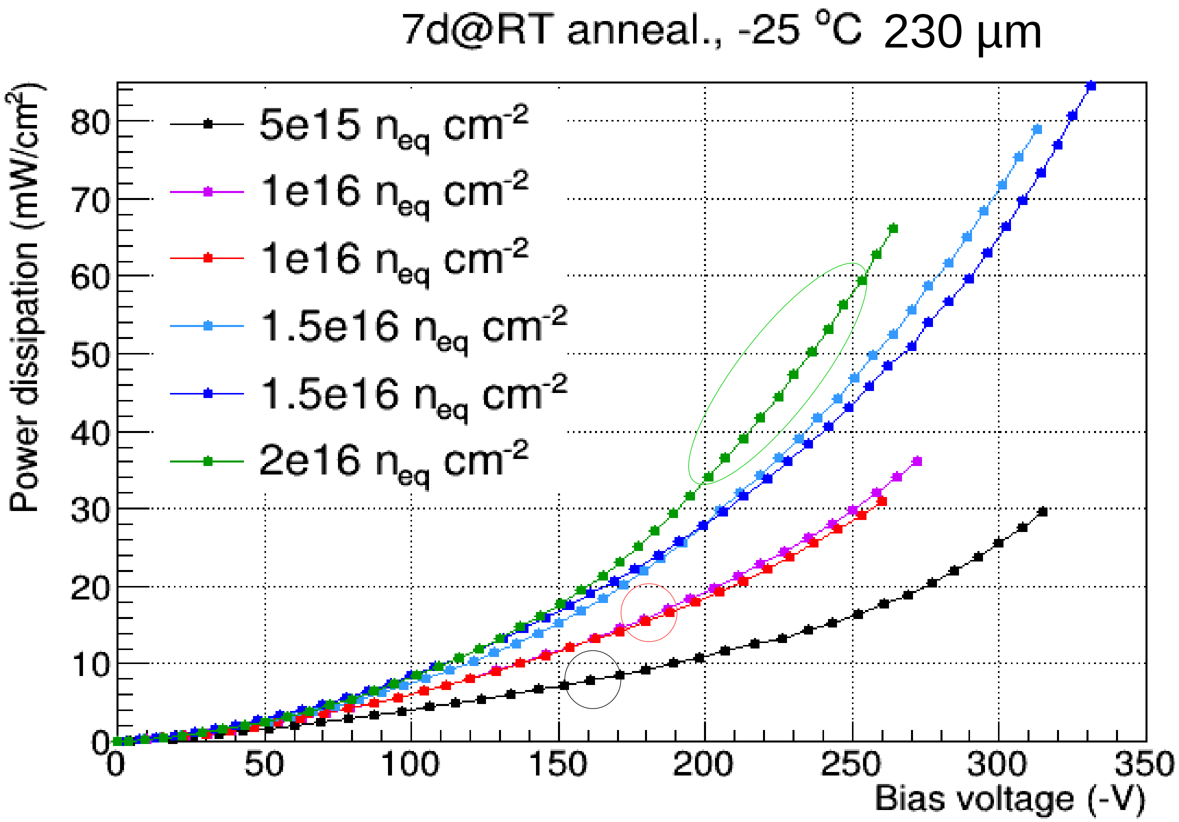


$$\frac{I}{I_0} = \left(\frac{T}{T_0}\right)^2 e^{-\frac{E_g}{2k_B}\left(\frac{1}{T}-\frac{1}{T_0}\right)},$$

where $E_g = \mathbf{1.2eV}, k_B = 8.62 \times 10^{-5}$eV/K

- Temperature scaling as expected (taking E_g=1.2 eV)
- Higher current when FEI3 chip is on due to heating up
  → corresponds to T increase by ~5 C

Power Dissipation



Fluence (neq/cm2)	Vop (V)	I (uA/cm2) [230 um]	I (uA/cm2) [150 um]	Power (mW/cm2) [230 um]	Power (mW/cm2) [150 um]
1E15	50	6	4	0.3	0.2
5E15	160	46	30	7.4	4.8
1E16	**180**	**83**	**54**	**14.9**	**9.7**
2E16	*200*	*160*	*104*	*32.0*	*20.8*
2E16	*250*	*220*	*144*	*55.0*	*36.0*

- Critical parameter for cooling and stave/service design
  - Should be as low as possible
- ATLAS ITk baseline T of -25 C
- At 1e16 n_{eq}/cm^2 and V_{op}=180 V
  - 15 mW/cm^2 at 230 µm
  - 10 mW/cm^2 scaled to ATLAS ITk benchmark thickness of 150 µm (validity of scaling demonstrated on next slides)
- Significantly lower than for planar devices
- For smaller electrode distance
  → expect lower V_{op}
  (for same thickness)
  → improved power dissipation

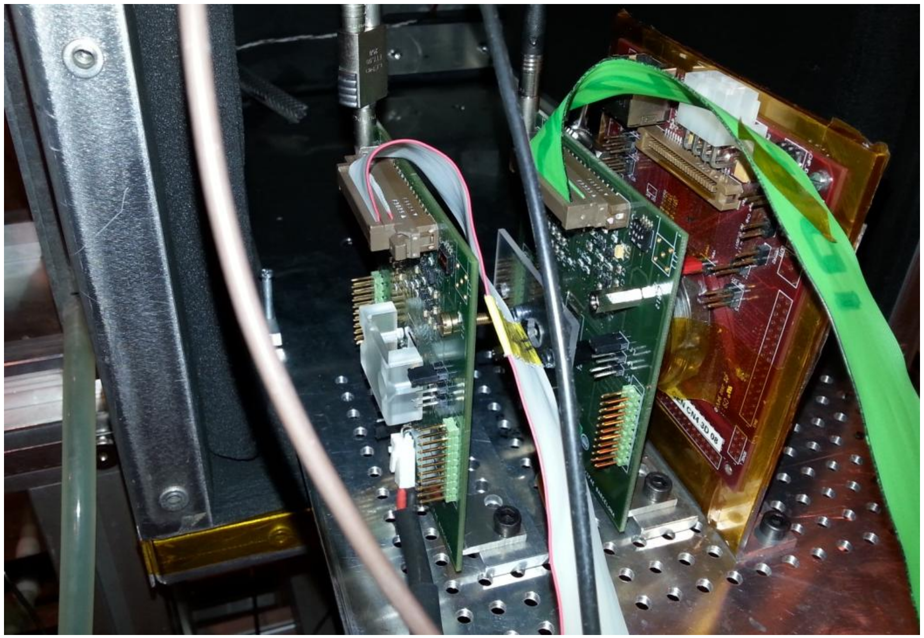
Compilation of Current and Power Dissipation

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	36	5.6
		23 MeV p (KIT)	CNM97 FEI4 Pixel [2]	230	67	13	41	6.6
		23 MeV p (KIT)	FBK11/87 FEI4 Pixel [2]	230	67	11	39	6.1
		n (Ljubljana)	CNM81 FEI4 Pixel [2]	230	67	13	48	7.6
		23 MeV p (KIT)	CNM strip 1 [3]	285	57	13	43	6.8
		23 MeV p (KIT)	CNM strip 2 [4]	285	57	13	44	7.0
		23 MeV p (KIT)	FBK strip [5]	230	57	11	40	6.4
		n (Ljubljana)	CNM diode [6]	50	57	6	50	8.0
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	90	16.2
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	165	33.0

- 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. 41% 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

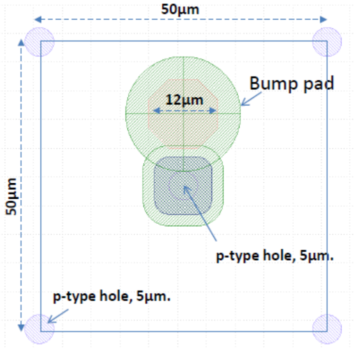
Beam Tests



- Tried to measure FEI3 hit efficiencies in beam tests in July and September
- Not straight forward anymore to operate FEI3 in beam tests with EUDET/AIDA telescopes
  - Seem to be very sensitive to noise and high rate
  - Eventually working
- Took a few runs for 1e16 n_{eq}/cm^2 FEI3 device
  - Analysis on-going
- More runs planned at next beam tests

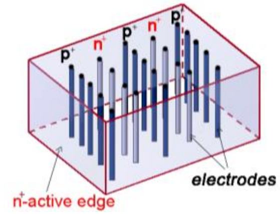
Conclusions

- First time studied 3D pixel detectors up to HL-LHC fluences
  - Here: neutron irradiated FEI3 up to 2e16 n_{eq}/cm^2
  - Next talk: proton irradiated FEI4 up to 9e15 n_{eq}/cm^2
- Even IBL/AFP generation of pixel detectors shows good performance
  - MPV~4 ke and CCE>20% at 2e16 n_{eq}/cm^2 for 2.5 ke FEI3 threshold
    → expected to improve significantly at 1 ke HL-LHC threshold
    and 35 µm electrode distance
  - Leakage current at V_{op} close to model expectations from bulk current
  - Excellent power dissipation:
    15 (10) mW/cm^2 at 1e16 n_{eq}/cm^2 for 230 (150) µm thickness and -25 C
- New 3D production runs on-going
  - Smaller pixel size and electrode distance, thinner, smaller columns
    → expect improved performance
  - First results expected early next year

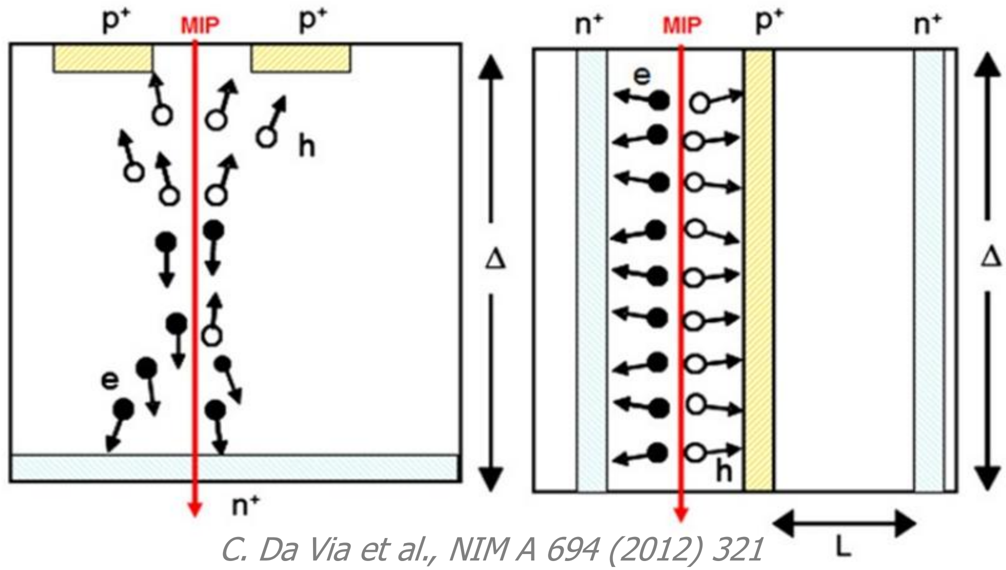


BACKUP

3D Detector Principle



Planar Technology | 3D Technology



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

Radiation-hard and active/slim-edge technology

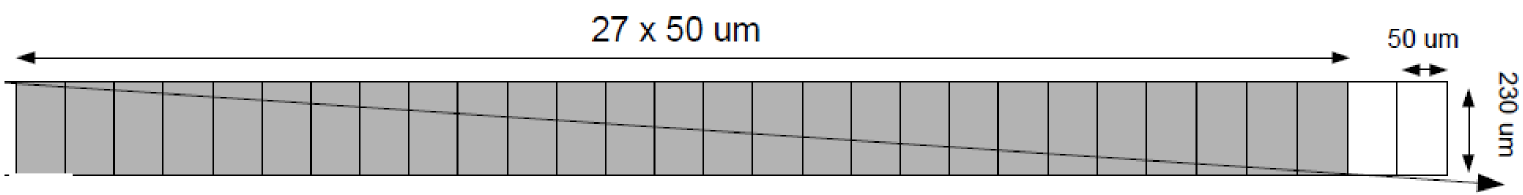
- **Advantages**
  - Electrode distance decoupled from sensitive detector thickness
    → lower $V_{depletion}$
      → less power dissipation, cooling
    → smaller drift distance
      → faster charge collection
      → less trapping
  - Active or slim edges are natural feature of 3D technology
- **Challenges**
  - 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

HL-LHC Studies: High Eta

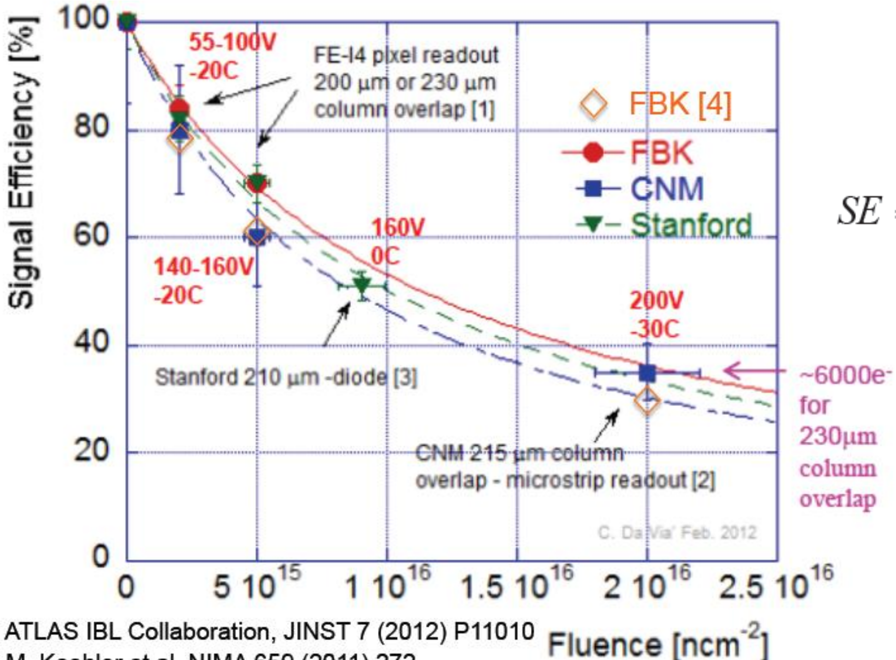
- Large clusters → large total charge → efficiency for whole cluster not a problem
- But for 50 μm pitch very small charge deposition per pixel (almost parallel tracks): 3300 e
- Testbeam campaign to measure CNM+FBK IBL FE-I4 devices with 80 angle in short pitch direction (50 μm)
  - 1000 + 1500 e threshold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

See talk by Ivan Lopez

80 (η=2.4) → Q=3300 e/pixel (50 μm)



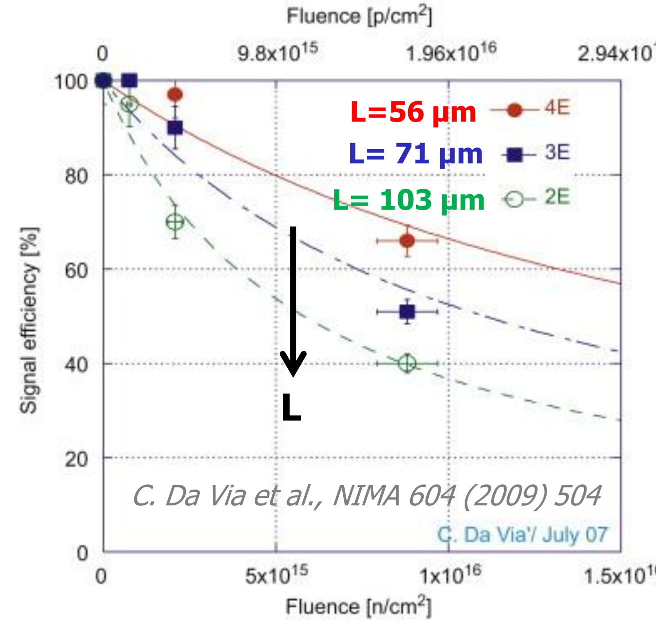
R&D Performance Summary

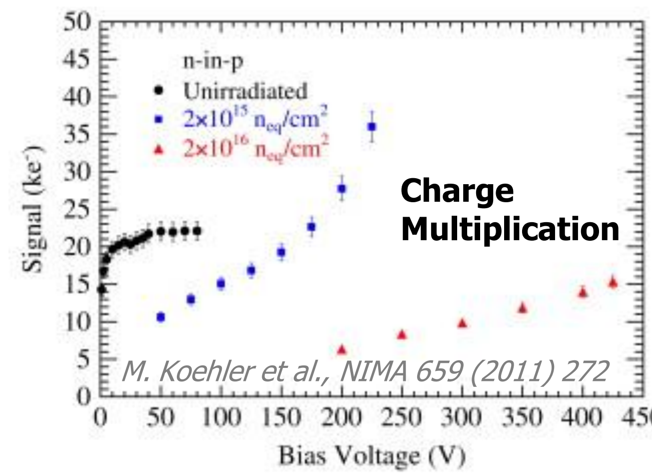


[1] ATLAS IBL Collaboration, JINST 7 (2012) P11010
[2] M. Koehler et al. NIMA 659 (2011) 272
[3] C. Da Via, et al., NIMA 604 (2009) 505
[4] G.-F. Dalla Betta, et al., HSTD9 (2013)

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

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





- Signal efficiency (SE) of 60-70% at $5\text{x}10^{15}$ n_{eq}/cm^2 and 30% at $2\text{x}10^{16}$ 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