12th «Trento» Workshop on Advanced Silicon Radiation Detectors
FBK, Trento , Italy
February 20 -22 , 2017

Pixel Detectors Development for CMS Phase-2 Upgrade

A. Messineo, Università & INFN sez. di Pisa

On behalf of the INFN-R&D Phase-2 and CMS Tracker collaborations

Sensor R&D programs in CMS

- R&D projects plan: *design of thin, radiation tolerant, small pitch pixel sensors*

  - **Phase-2 (High-Luminosity LHC) challenges:**
    - Luminosity of $5x10^{34}$ $cm^{-2}s^{-1}$, up to 200 events/25 ns bunch crossing
    - Maintain occupancy at ≈ % level and increase the spatial resolution
      - Pixel size ~ 25x100 μm^2 or 50x50 μm^2 (currently 100x150 μm^2)
    - Radiation level for the 1st pixel layer after 3000 fb^{-1}
      - $\Phi_{eq} \approx 2x10^{16}$ cm^{-2}, dose ≈ 10 Mgy

  - **Two technology approaches**
    - ***Planar Pixel***
      i. INFN – FBK R&D program, ATLAS & CMS common (n^+-p)
      ii. CMS tracker collaboration, HPK submission (n^+-p)
    - ***3D columnar Pixel***
      i. INFN – FBK R&D program, ATLAS & CMS common (n^+-p)
      ii. CNM Barcelona (*see Gomez talk*)

INFN-FBK R&D pixel Phase-2 Project

- **R&D aim:** ***Design and production of pixel detectors for innermost layers of HL-LHC trackers***
  - **Partnership: Fondazione Bruno Kessler-FBK (Trento, Italy)**

- **Device technologies:**
  - Planar n-in-p *(see S. Ronchin poster)*
    - Process Options: p-spray and/or p-stop
    - Periphery design: standard and A/T-Edge.
  - 3D Columnar n-in-p *(see R. Mendicino talk)*
  - Devices are designed in collaboration with FBK, Single Sided processing optimized by FBK.

- **Prototypes assembly main features:**
  - Hybridization on chip via Bump Bonding : SnAg[(1)] and Indium[(2)]
  - Thinning after processing: **smallest total sensor thickness 180 µm**[(1)]
  - Spark protection: on Sensor (periphery) and ROC (periphery or whole area) by a patterned BCB (Benzo-Cyclo-Butene) layer ~2 µm thick[(1)]

[(1)] *IZM Fraunhofer, Berlin*
[(2)] *Leonardo Finmeccanica, Roma*

INFN-FBK R&D pixel Phase-2 Project

- ***Production and tests***:
  - Two Planar and one 3D columnar pixel batches produced In collaboration with FBK
  - Prototypes qualified in laboratory and in three beam test sessions
  - One neutron and proton irradiation done

Team:

Design, processing, qualification, assembly…

M. Boscardin, G. Giacomini[(1)], S. Ronchin (FBK Trento)
G.F. Dalla Betta, D.M.S. Sultan (Trento)
M. Meschini,(Firenze)
A.Messineo, R. Dell'Orso (Pisa)
F. Ravera, A. Solano (Torino)

[(1)] Now at BNL

Test Beam and Data Analysis

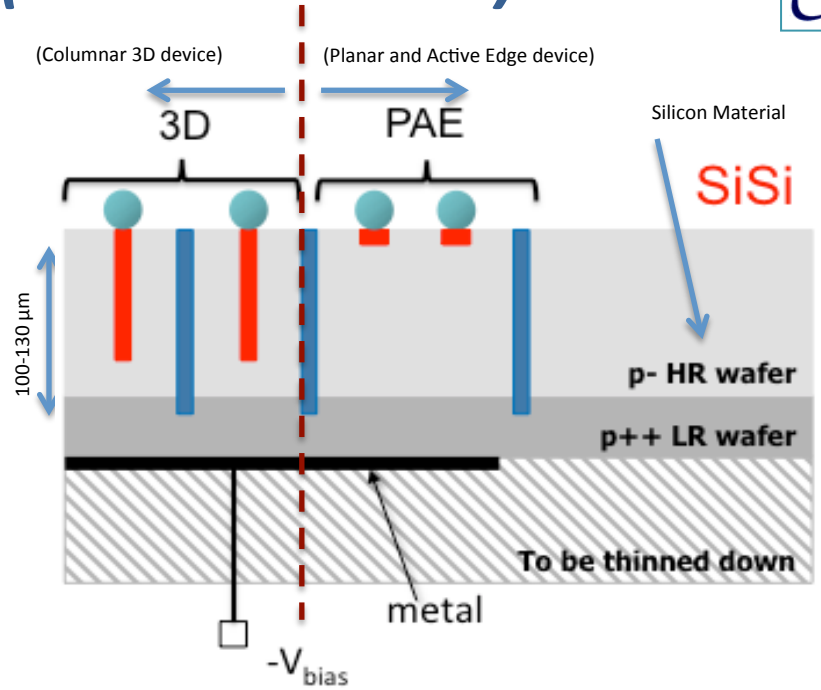
M. Dinardo, L. Moroni, D. Zuolo (Milano B.)
C. Civinini, M. Meschini, G. Sguazzoni L. Viliani,
I. Zoi[(1)] (Firenze)
L. Uplegger, C. Vernieri (FNAL)

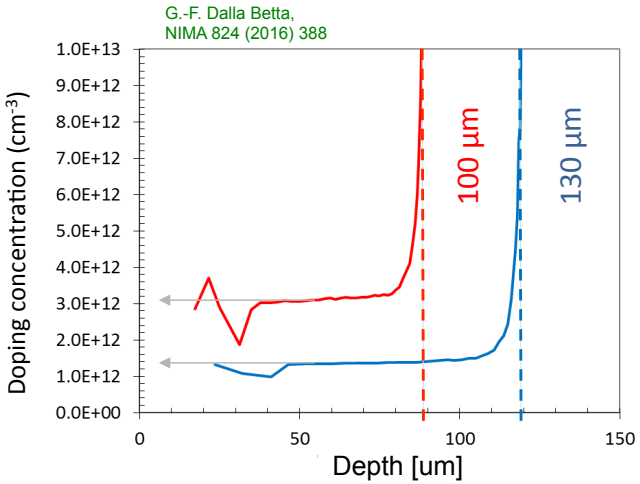
[(1)]Now at Hamburg Univ.

Material features (Planar and 3D)

- Material:
  - Silicon wafers, 6-inch, FZ p-type resistivity > 3 kOhm cm, wafers Si-Si Direct Wafer Bond and SoI[(1)]
    - Thin active bulk: 100 µm and 130 µm

[(1)] *Icemos Technology, Belfast*





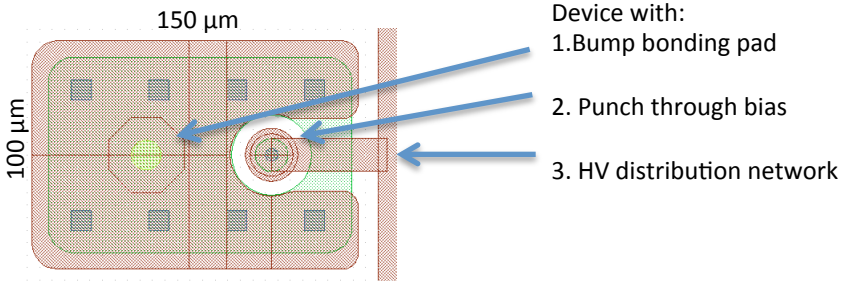
Doping concentration profile measurement: effective thickness reduced by the Boron diffusion (for SiSi) from wafer carrier deep about 10 µm.

- dE/dx reduced for thin silicon layer
  - Down to ~ 60% of most probable energy loss (388 eV/µm)
- Charge collection reduced by Boron diffusion
  - At Beam test ~6000 (100 µm) ~8000 (130 µm) electrons expected
    - Measured by the CMS pixel Phase-1 ROC PSI45dig: threshold ~1500 e + dispersion ~120 e

INFN-FBK R&D: Planar Pixel Devices

- **Device design details, standard pixel**:
  - CMS/ATLAS standard ROC pitch pixel devices, assembled in prototypes using ROCs available today

- **Standard** Pixel prototype (CMS)
  - CMS Phase-0 design
  - 100 µm X 150 µm pitch (4160 Cells)
  - Can be Readout by
    - PSI46dig ROC (Phase-1) Rad.-Qual.: 2.5 MGy
    - PROC600 R-Q: 5 MGy

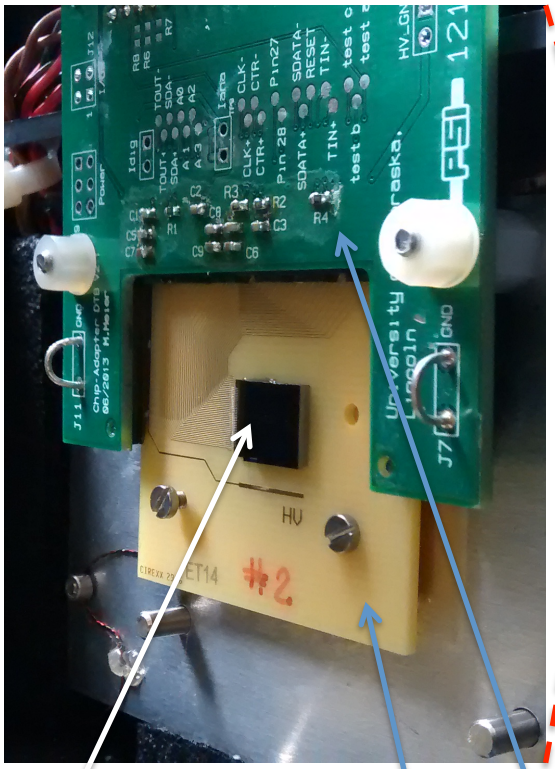


- **Device design details, small pitch pixel**:
  - Phase-2 pitch pixel devices adapted to standard ROC,
  - Phase-2 pitch pixel devices for new ROC chip.

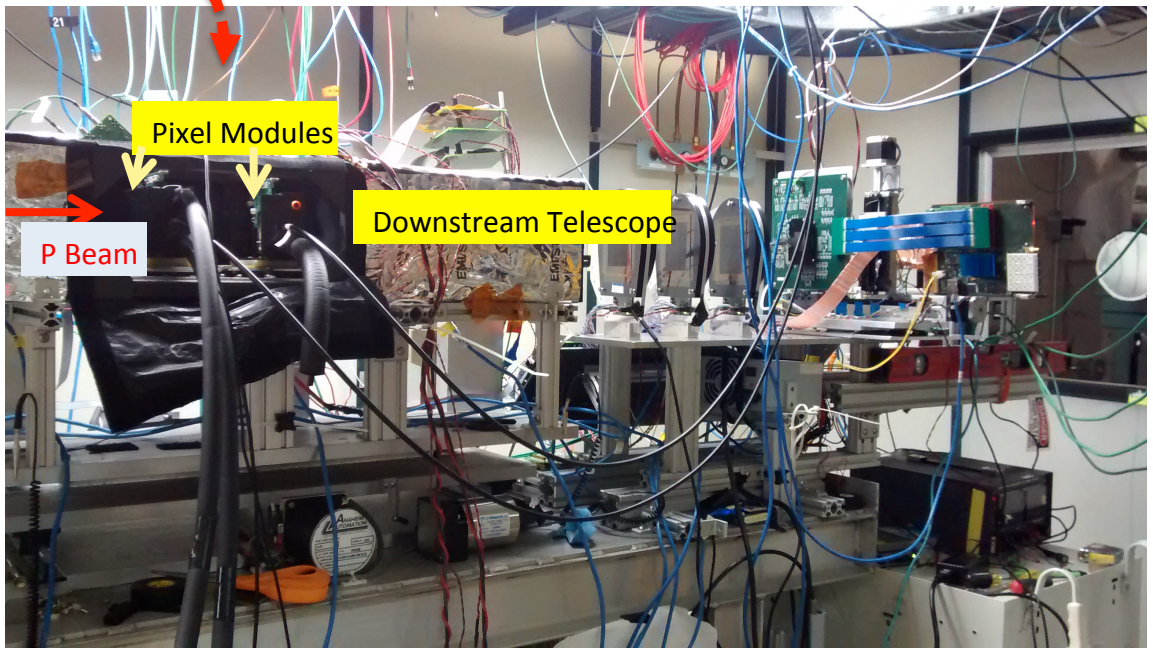
- Design includes devices to be assembled with next generation ROCs
  - ROC4sens (PSI)
    - **IBM 250 nm, 50 x 50 µm²** , 155 x 160 pixels, no charge threshold, rad hard > 5 MGy, operated with CMS pixel test board, **staggered BB pattern**, available since summer 2016 (on PROC600 wafer)
  - RD53A (RD53 collaboration):
    - **65nm, 50 x 50 µm²** , 400 x 192 pixels, min. threshold: 600 e- , rad hard up to 10 MGy **non-staggered BB pattern,** availability later 2017

Beam Test experiment

- Beam test done at the MTest test beam facility in Fermilab (US)
  - Beam: 120 GeV protons from Main Injector
- Tracking pixel telescope
  - 8 CMS pixel planes (pixel cell: 100x150 μm^2)
  - Readout by PSI46 analog chip
    - Tracking performance: ~8 µm resolution for the extrapolated track on each coordinate
      - *Ref. NIM-A 811 (2016) 162-169.*
- DUT fixed to an optical bench with step rotation, HV, FNAL-Captan DAQ and active cooling at −20°C

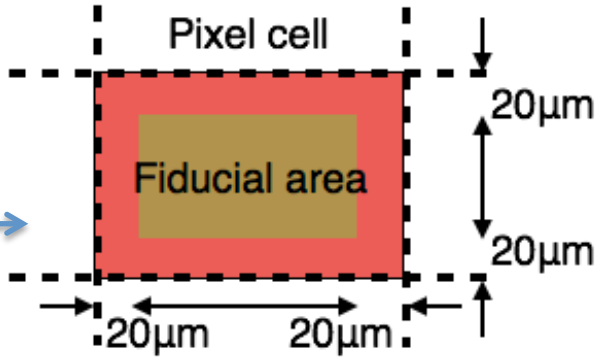


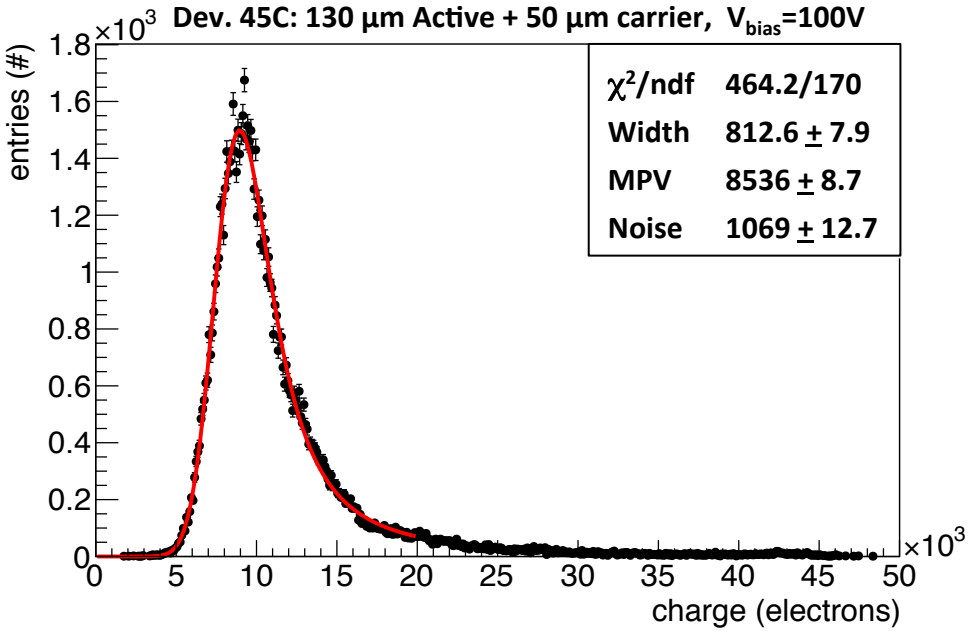
- Typical prototype
  - Assembled on PCB
    - Connecter to DAQ board

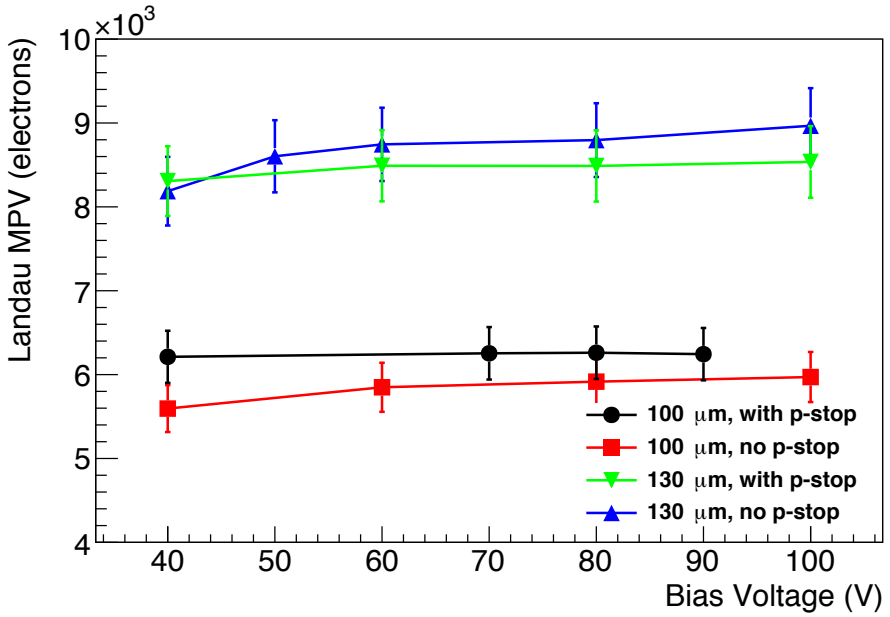


Beam Test: charge collection

- **Standard** pixel prototype
- Require single pixel clusters
- Tracking pixel telescope selection:
  - the predicted track impact point should be located ± 20 µm far from pixel cell edges (two sides)
- *Standard* quality cuts on tracks
  - Fit with Landau convoluted with Gaussian



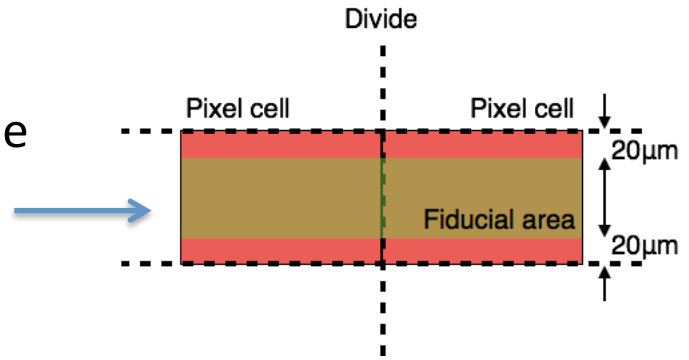




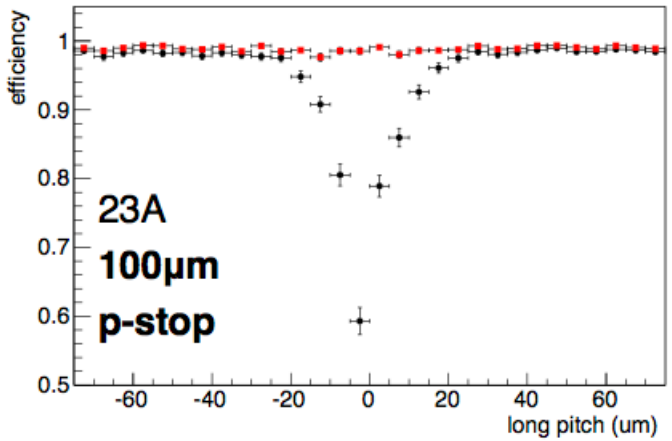
Averaging over full sample the Ratio MPV@130um / MPV@100 is ~1.38 , expected [1.2-1.44]

Beam test: charge sharing neighboring pixels

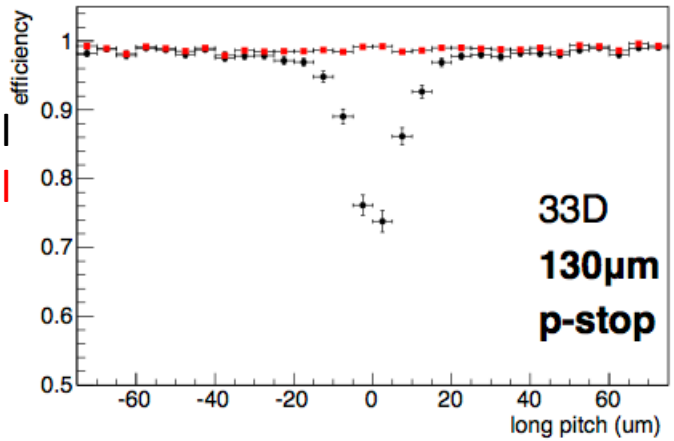
- **Standard** pixel prototype
- Tracking pixel telescope selection:
  - the predicted track impact point should be located ± 20µm far from pixel cell edges (one side)
- *Standard* quality cuts on tracks



V_{bias}=40V



- Hit of pointed pixel
- Hit of pointed pixel or hit in closest pixel on same row



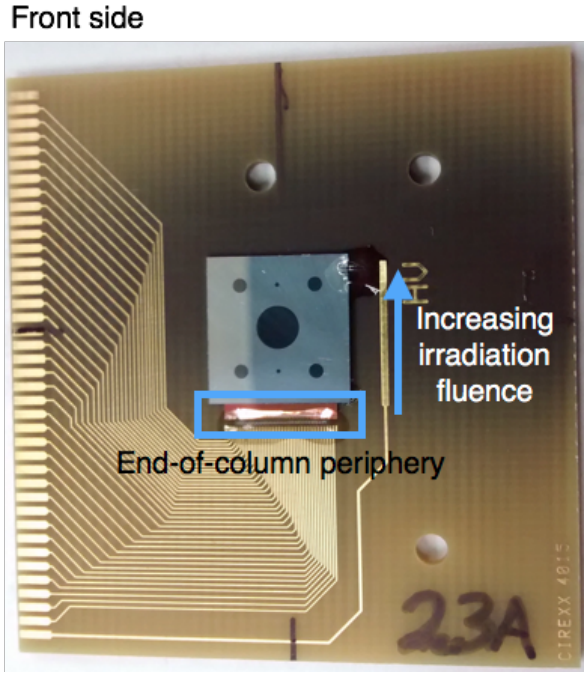
- Standard thin detectors fully efficient in both views: long pitch (row direction) and short pitch (column direction)

Device Irradiation

- Irradiations:
  - Los Alamos 800 MeV protons
  - Neutron irradiated Ljubljana-reactor [(1)]
  - CERN proton irradiation 24 GeV protons

- Irradiation done after Flip Chip assembly
  - Constraints from radiation tolerance of PSI46 Digital ROC ~250 Mrad

- Results affected by
  - Non uniform irradiation in case of charged particle beam
    - Non uniform radiation damage on ROC Pixel Unit cells
  - Different activation of damage on ROC for charged particles vs neutron



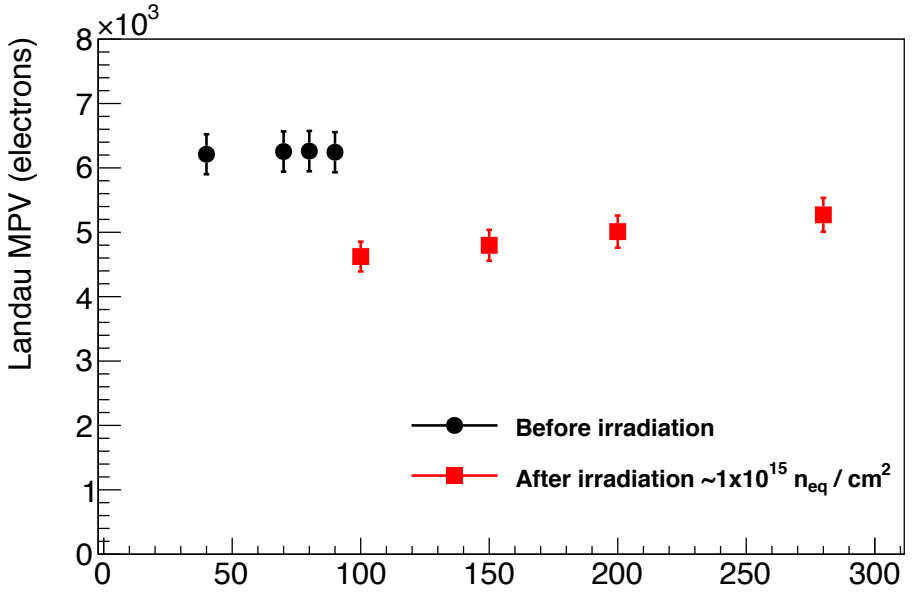
- Radiation level measured by in situ dosimetry and corrected (normally scaled down) by simulation predictions
  - Effective Fluences (today) between ~2×10^{14} n_{eq}/cm^2 and ~2.7×10^{15} n_{eq}/cm^2

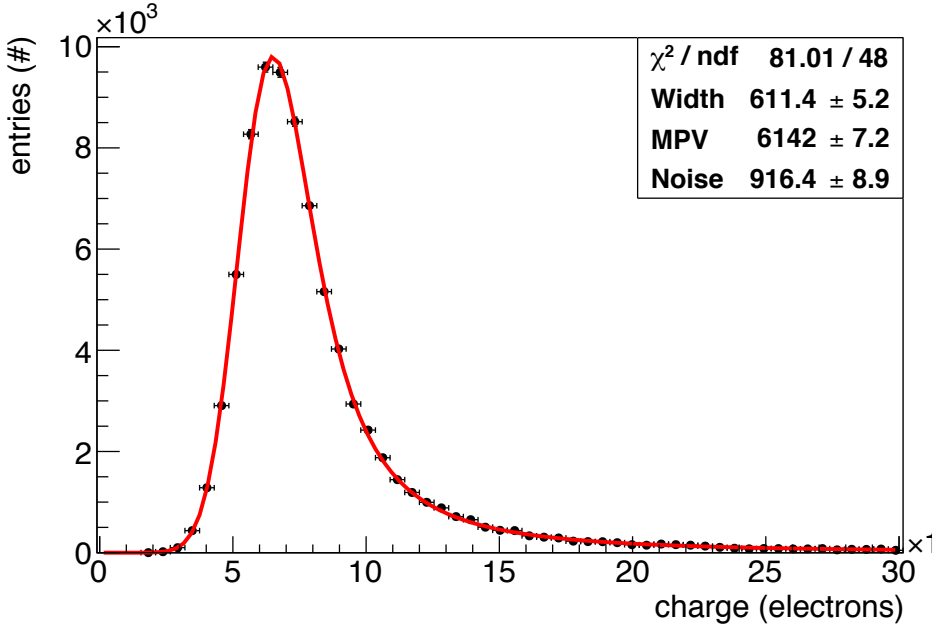
- Planned irradiation for non bump bonded pixel sensor
  - post irradiation low-T Flip Chip assembly (Indium)

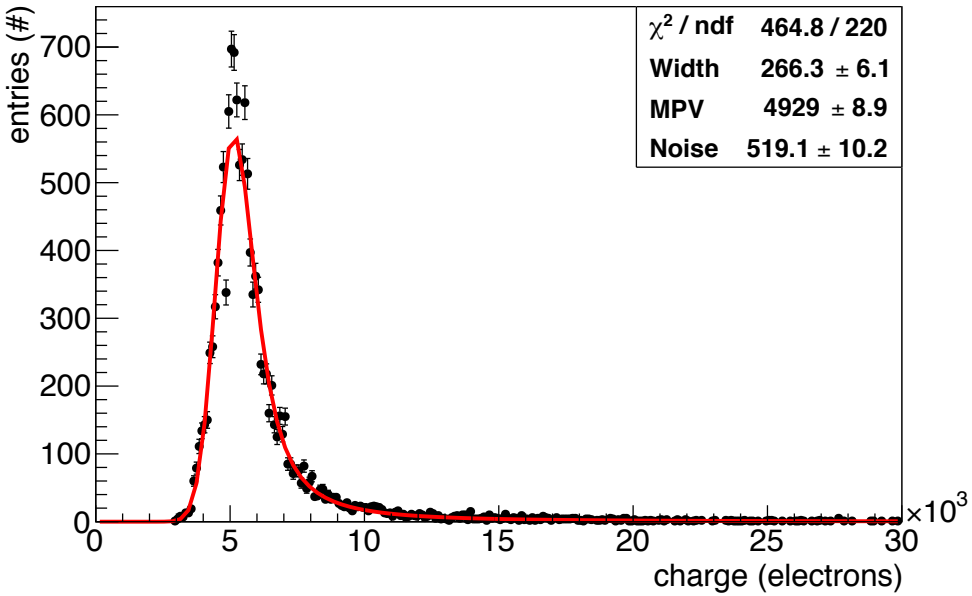
[(1)] Irradiations at JSI (Ljubljana) were supported by the H2020 project AIDA-2020, GA no. 654168, TNA. Thanks to V. Cindro and colleagues.

Radiation damage: planar pixel

- **Standard** pixel prototype
  - 100 µm active thickness
- Neutron irradiation
  - 1×10^{15} n_{eq} / cm^2
    - ~20 % of charge loss observed at 280V (safer operation)
    - Temperature -20 °C

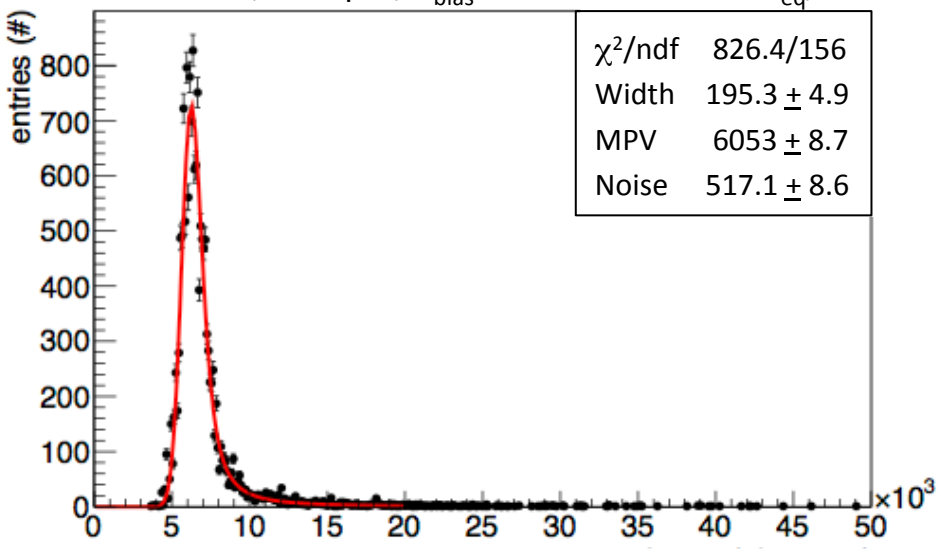




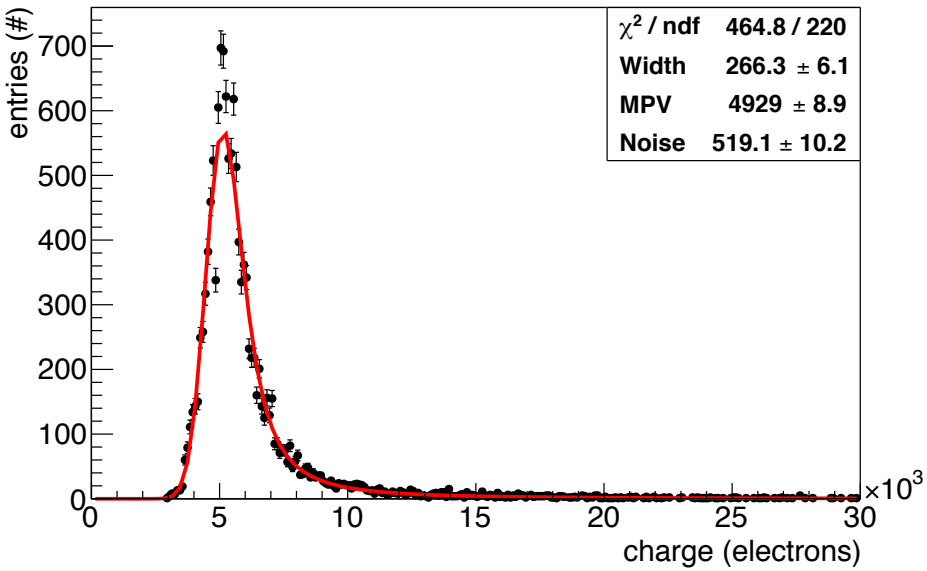


Radiation damage: proton irradiation

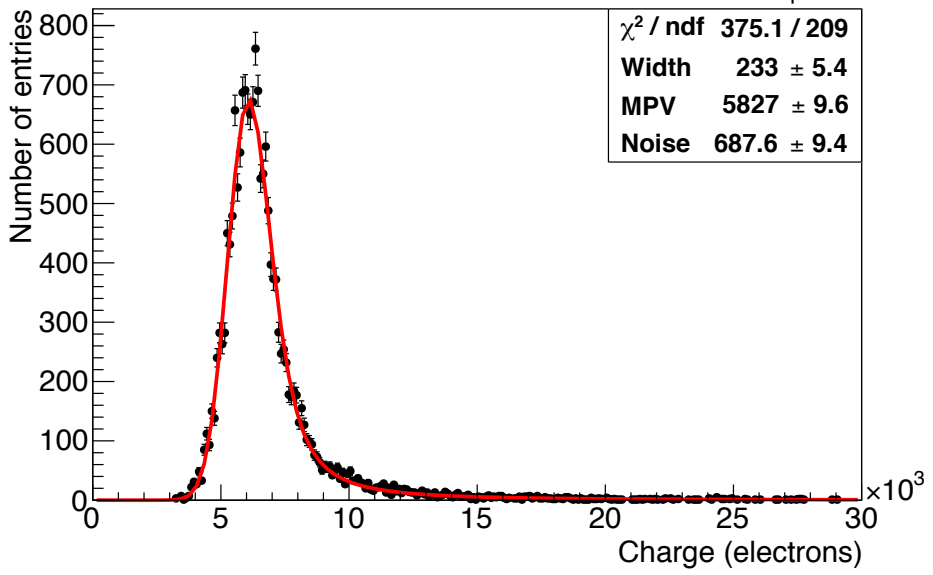
Dev. 45B, 100 µm, V_{bias}=400V Φ~0.2x10^{15} n_{eq}/cm^2



Dev. 43B, 100 µm, V_{bias}=280V Φ~1.0x10^{15} n_{eq}/cm^2



Dev. 53B, 130 µm, V_{bias}=300V Φ~1.2x10^{15} n_{eq}/cm^2



- **Standard** pixel prototype
  - Fluence Corrected for non uniformity of the beam spot on device
  - Charge collected at the highest available voltage, Temperature -20 °C
    - New beam test on going

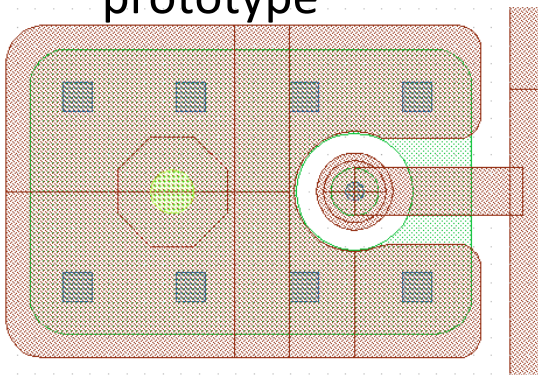
Dev. Thick. (µm)	Fluence (10^{15})	Vbias(V)	Charge loss
100	**0.2±0.03**	**400**	**4.4%**
100	**0.9±0.14**	**280**	**19.7%**
130	**1.15±0.17**	**300**	**25.9%**

- Apparently thin detector seems to be more radiation tolerant, however the thick detector should be at under-depletion at the highest V_{bias} =300V

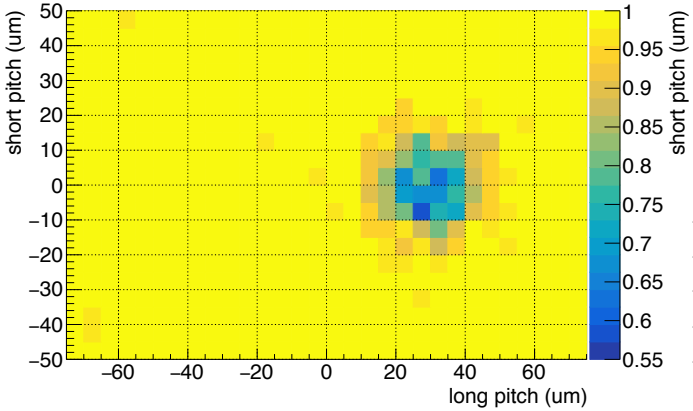
Pixel cell design details

- Tracks detection efficiency is affected by the pixel bias structure

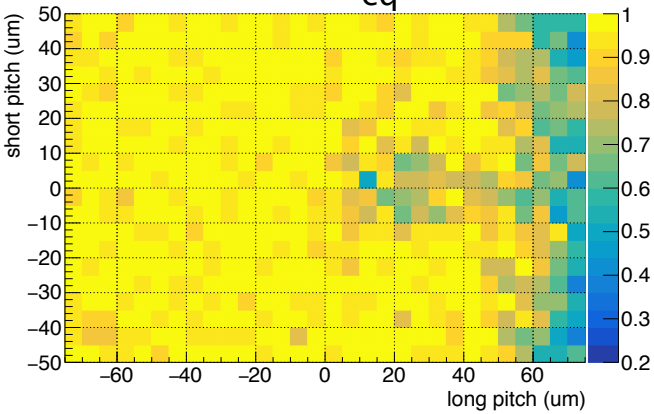
- **Standard** Pixel prototype



Pixel Unit Cell efficiency
Φ~0



Pixel Unit Cell efficiency
Φ~2x10^{14} n_{eq} / cm^2

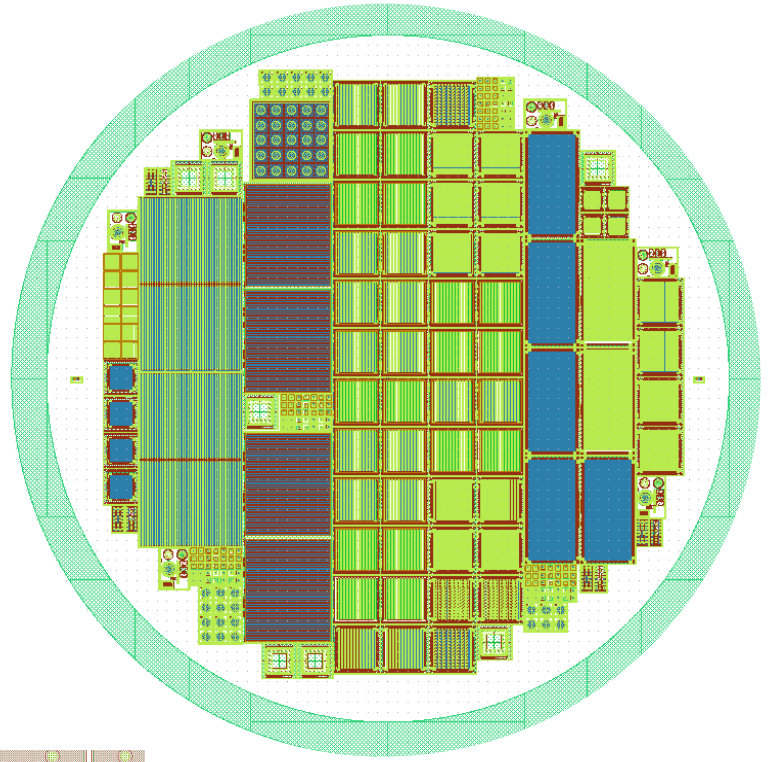


Dev. 45B

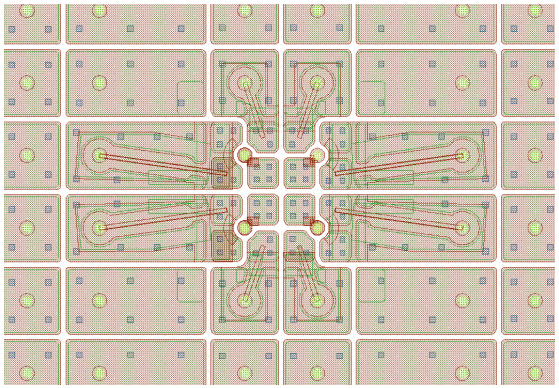
- Geometry of the bias structure or moderated p-spray mitigate the inefficiency before irradiation
  - Observed however after irradiation
  - Simulation study to optimize geometry/process of bias structure
    - For small pitch pixel design can be critical (i.e. common 4-fold bias dot)

INFN-FBK R&D project Submission on 6" n^+-p wafers

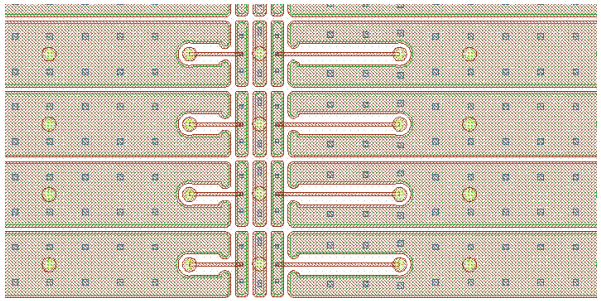
- Batch designed and produced
  - Now at qualification step
- Material
  - SiSi DWB and SoI 100 µm and 130 µm thick on carrier wafer
- Layout includes
  - Thin/Active edge periphery design
  - Standard ROC pixel 100 µm X 150 µm PSI46dig
  - Small pitch pixel adapted to standard ROC(1)
  - New ROCs: RD53A and Roc4sens FE-I4, CHIPIX65, FCP130



- (1)Device design example
  - Adapt small pitch to standard ROC pitch
    - All ROC readout channels are connected



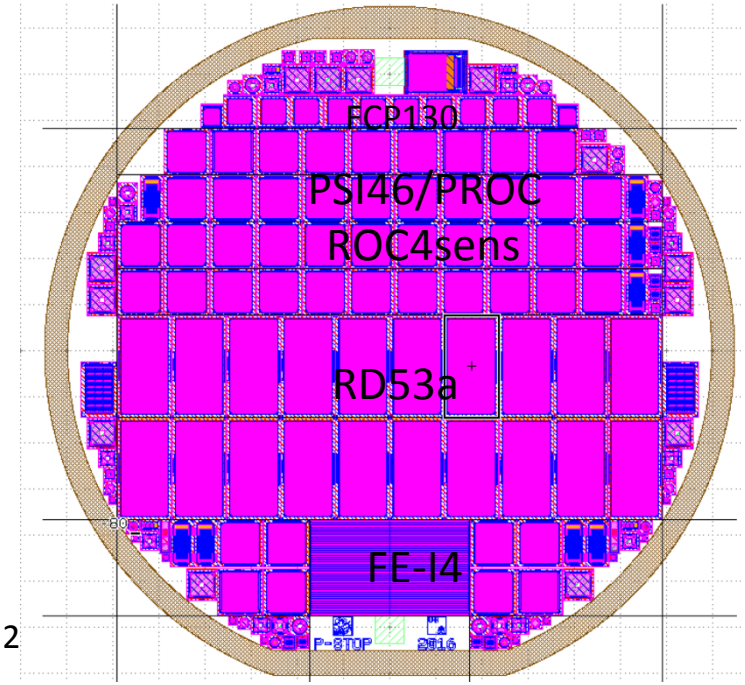
Adapt 50 µm X 50 µm:
4-fold readout cells



Adapt 25 µm X 100 µm:
three columns readout cells

CMS-common HPK Submission on 6” n^+-p wafers

- 35 wafers 6” n^+-p FZ, 3 materials
  - 150 µm, no handle wafer
  - 150 µm + 50 µm Si-Si direct bond
  - Deep diffused 150 µm + 50 µm
  - P-stop and p-spray isolation (only dir. bond)



Aims of the R&D submission:

- Evaluate pixel geometry: 25x100 vs. 50x50 µm^2
- Study and optimize sensor design
  - Pixel isolation: p-stop vs p-spray (rad-hardness)
  - Bias scheme for small pixels
    - no bias, common punch through, poly-silicon bias
  - Metal overhang to mitigate E-field
  - Signal routing

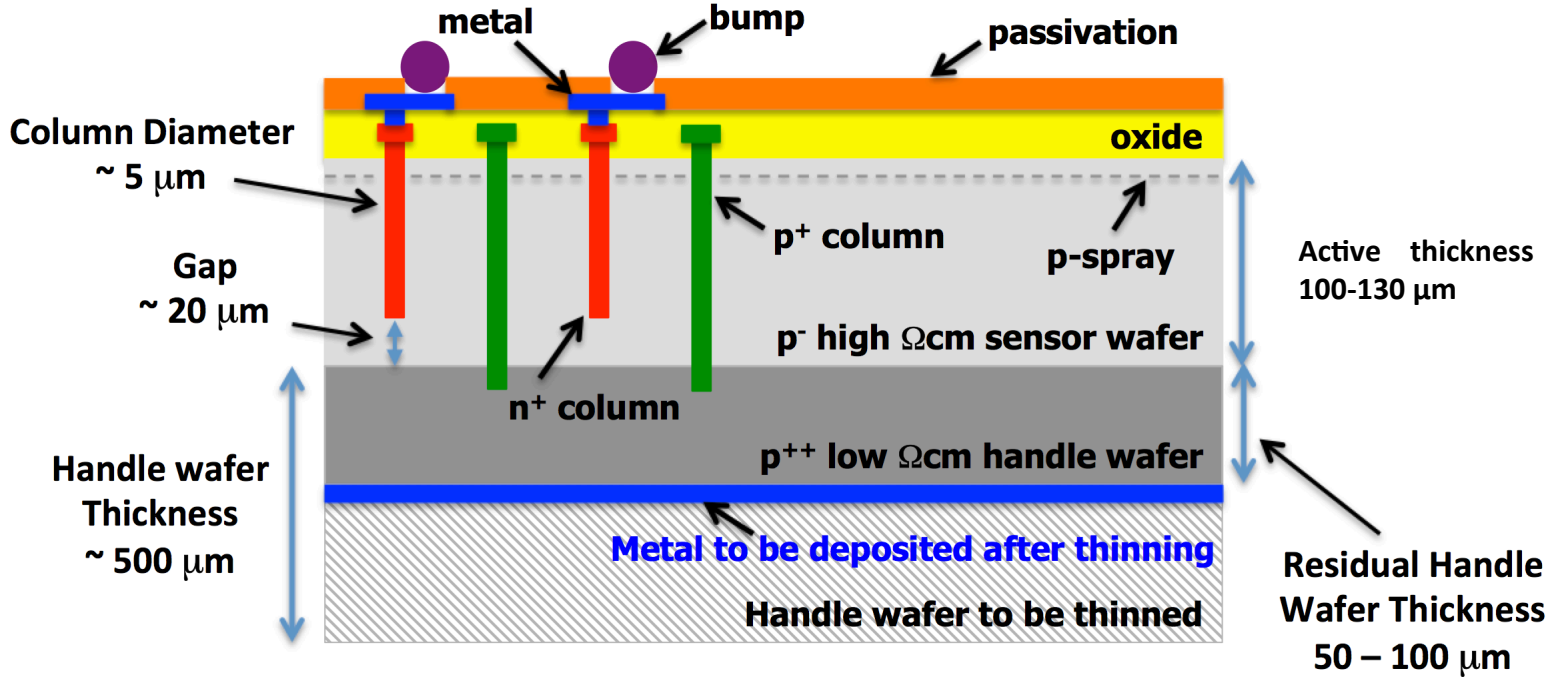
Pixel sensors for these r/o chips:

- PSI46/PROC600, ROC4sens, RD53a, FCP130, CHIPIX65, (FE-I4)

Design in collaboration with HPK, wafers expected back April 2017

INFN-FBK R&D: 3D columnar devices

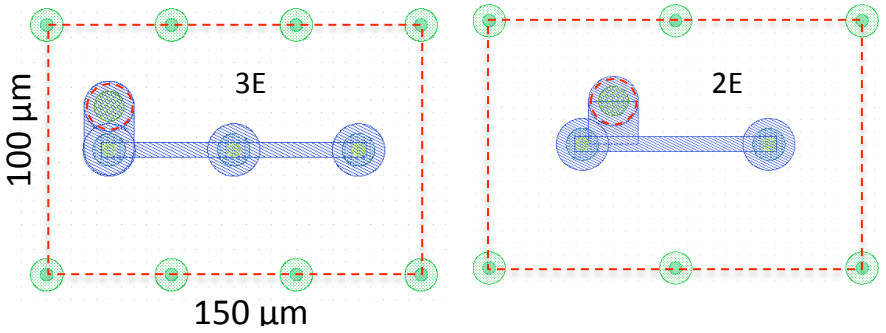
- Devices Single Sided processed: can be thinned
- Pixel Unit Cell design with variety of collecting electrodes
- Location of pad for bump bonding optimized



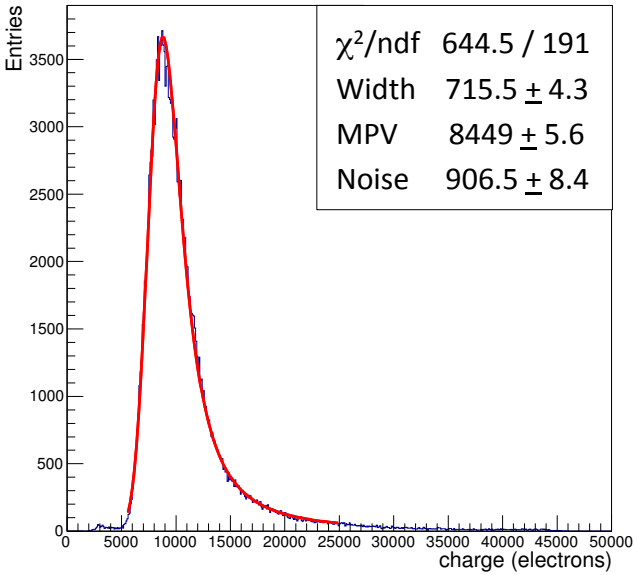
- **Standard** pixel prototype
  - 100 μm X 150 μm pitch
  - Readout by PSI46dig ROC (Phase-1)
  - 130 μm active thickness
- **Small pitch** pixel prototype
  - 50 μm X 50 μm and 25 μm X 100 μm pitch
  - Readout cell adapted for PSI46dig ROC (Phase-1)

Beam test: Charge collected 3D compared to planar

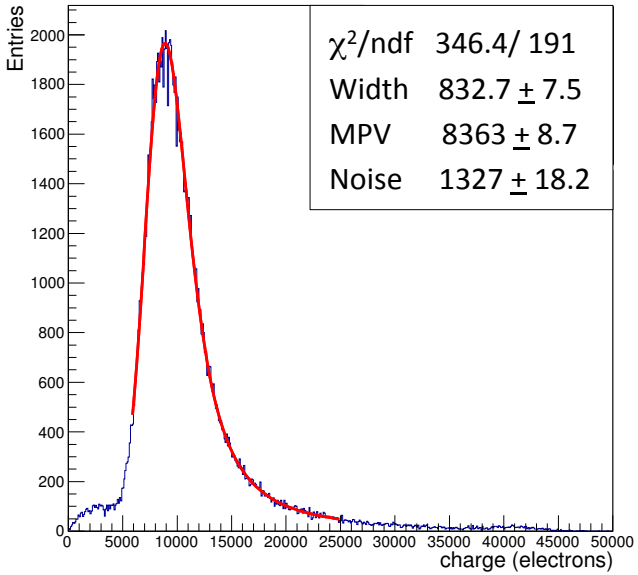
- **Standard** pixel prototype
  - 3D: cells with 3E or 2E junction column



- Planar and 3D prototypes used on the same beam test session



56D (3D) – 3E 100x150 µm @40V



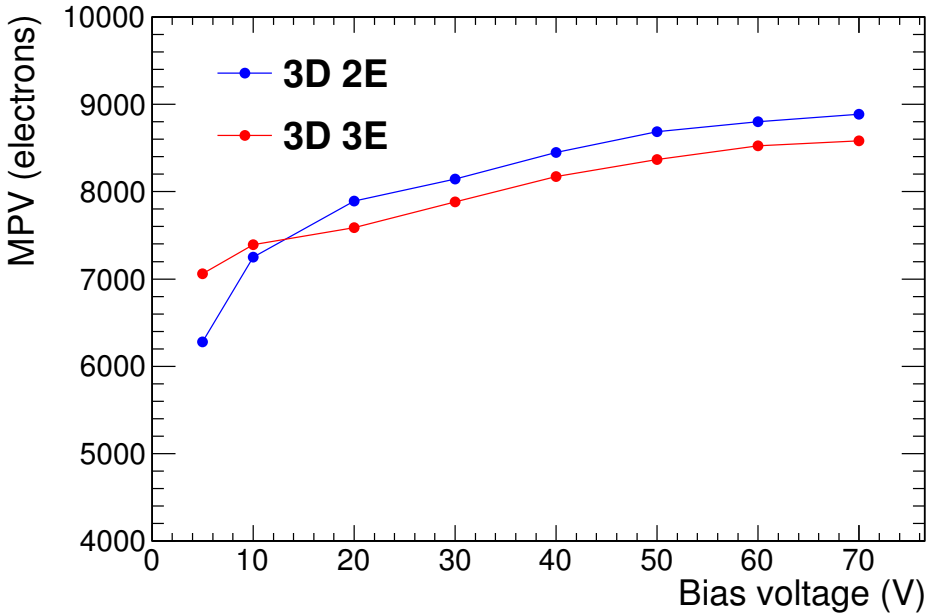
63D (Planar) – 100x150 µm@90V

- Charge collection performance on 3D columnar thin prototype comparable to planar thin one (@ higher V_{bias})

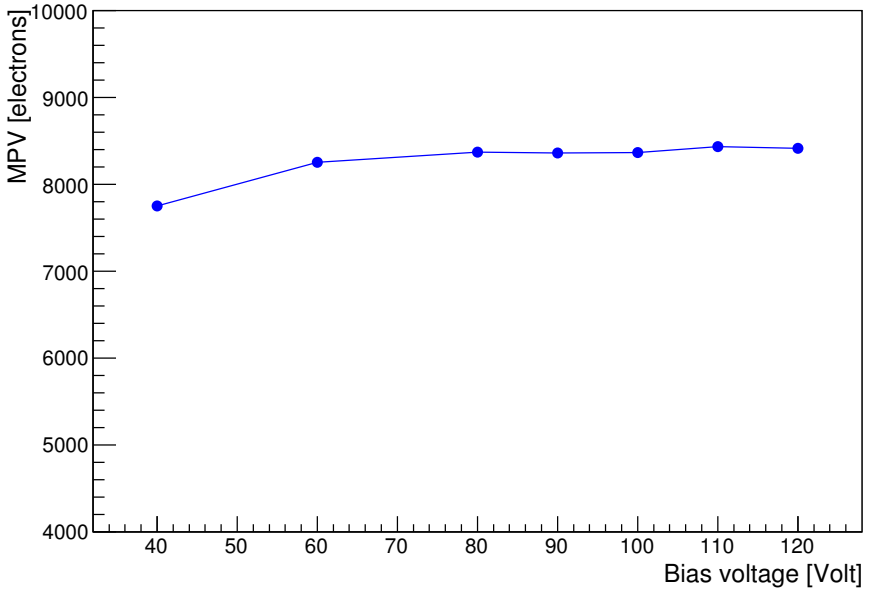
Beam test Charge collection summary

- **Standard** pixel prototype
- Tracks orthogonal to the detector
  - Standard track quality selection
  - Tracking telescope predicted track impact on the selected cell

Charge collected vs V_{bias} 3D pixels



Charge collected vs V_{bias} planar pixels

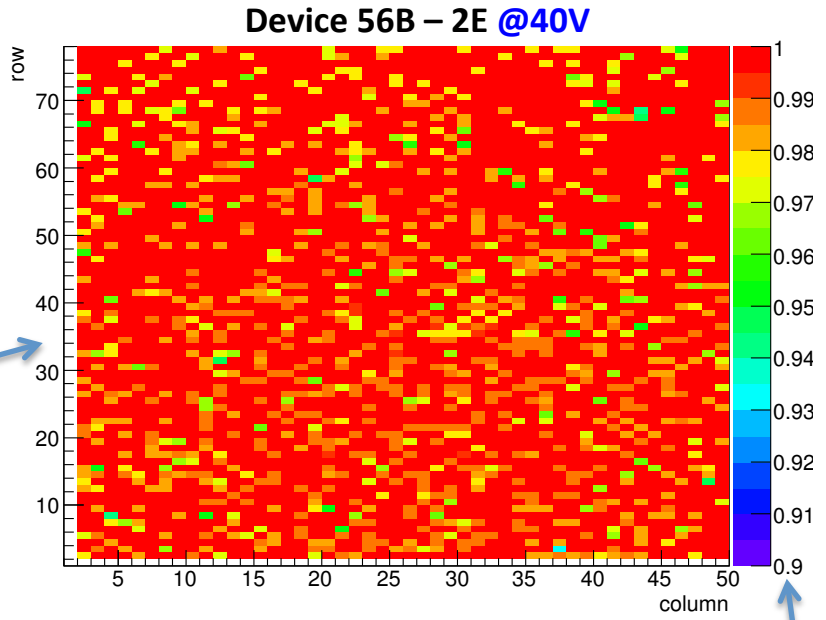


- Systematic uncertainties are not taken into account: 5%-10% expected
- Absolute calibration not applied: small variation ROC by ROC expected
  - ➢ Plan to measure the charge calibration factor by X-ray fluorescence (standard procedure)
  - ➢ New beam test measurement in order to improve statistic

Pixel 3D detector: hit reconstruction efficiency

- **Standard** pixel prototype
- Orthogonal tracks
  - Standard track quality selection
  - Tracking telescope predicted track impact on the selected cell or in the 8 neighborhood

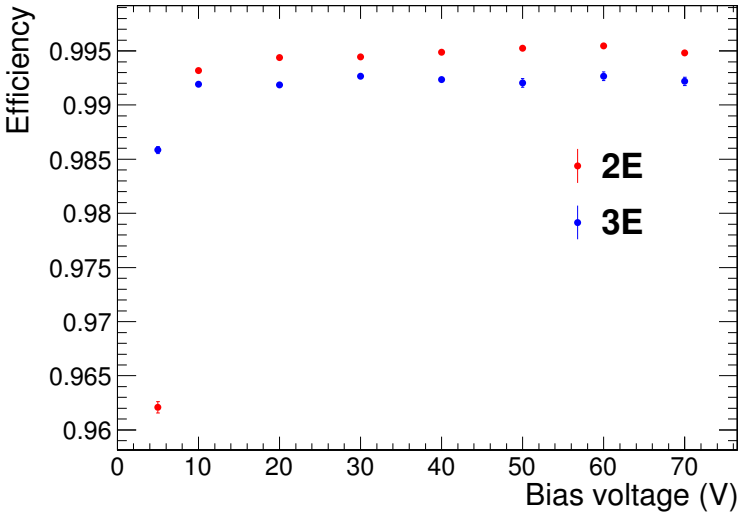
Hit efficiency: 2D map



Efficiency is very high and uniform

0.9

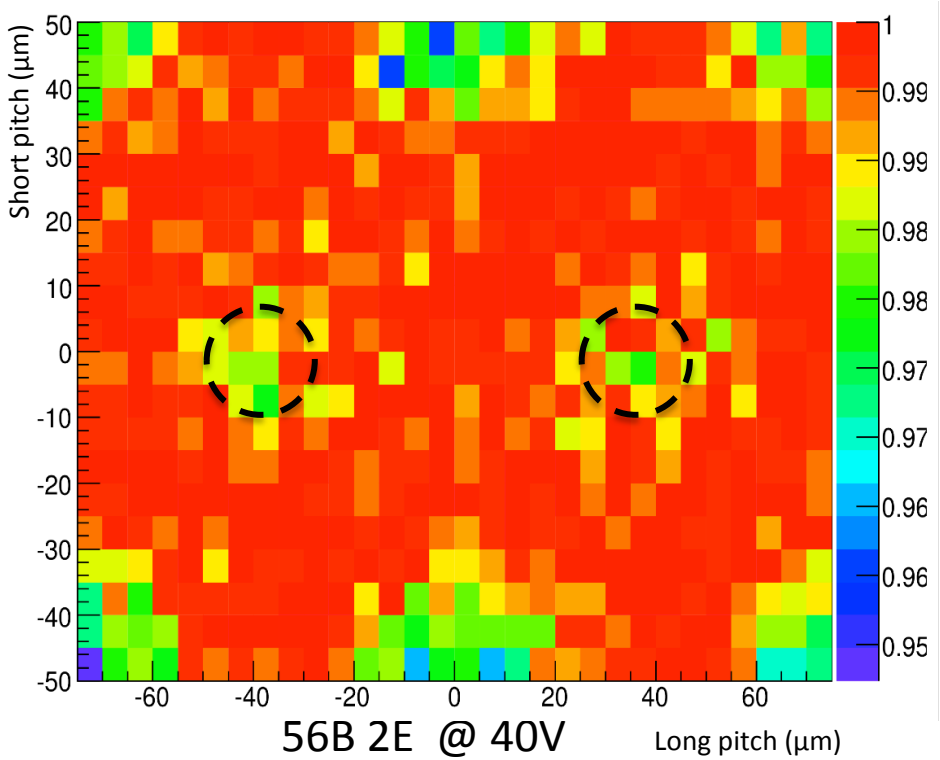
High efficiency also at low V_{bias}

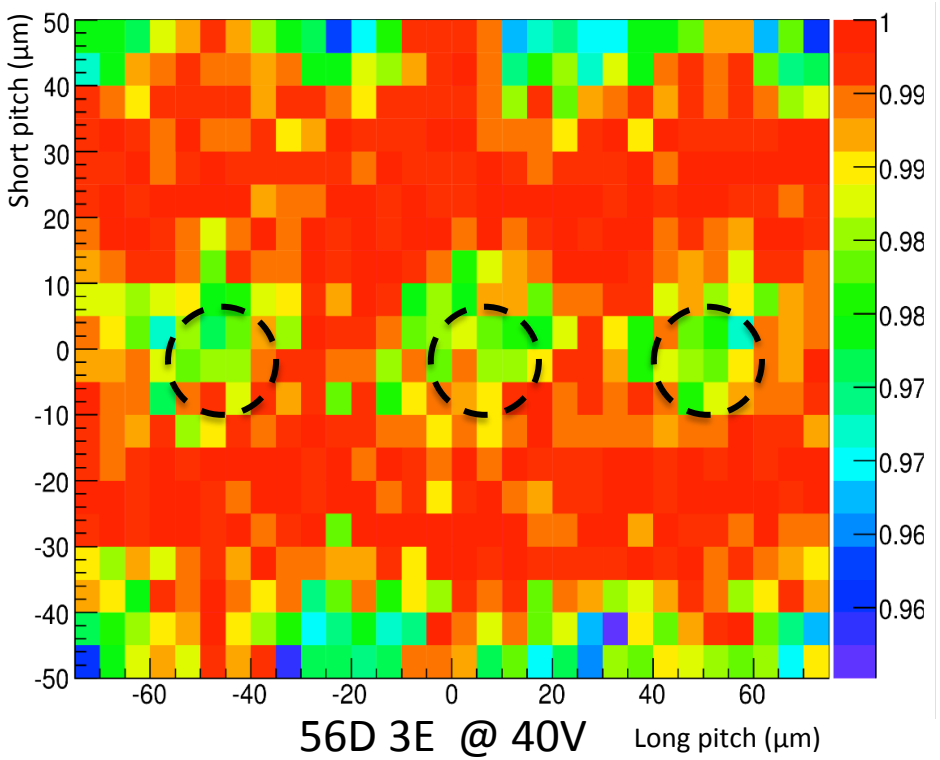


- Inefficiency from columns
  - 3E column eff. 0.9927±0.0002
    - Fraction of column area ~0.8%
  - 2E column eff. 0.9943±0.0002
    - Fraction of column area ~0.5%

Pixel Unit Cell: hit reconstruction efficiency

- **Standard** pixel prototype
- Different cell column design: 2 and 3 electrodes
- Orthogonal tracks
  - All Pixel Unit Cells (4160) overlapped on a single cell: hit efficiency 2D map

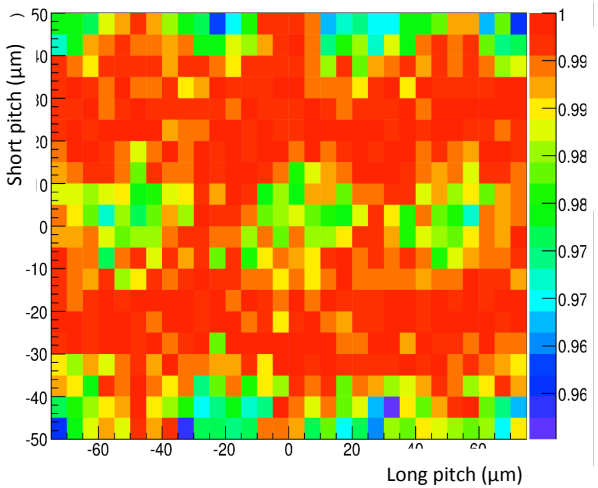




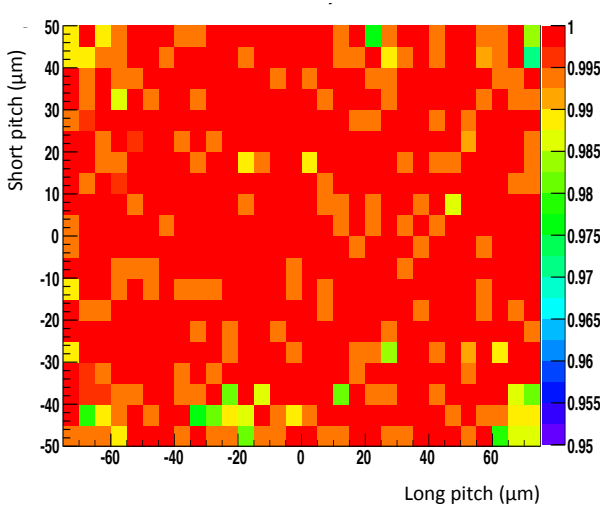
- Visible effect of columns (non collecting) volume
  - Smaller charge collection efficiency for tracks pointing to Junction columns
  - Lowest charge collection efficiency values located on tracks pointing to Ohmic columns (E_{field} ~0)

Pixel Unit Cell hit reconstruction efficiency: tilted

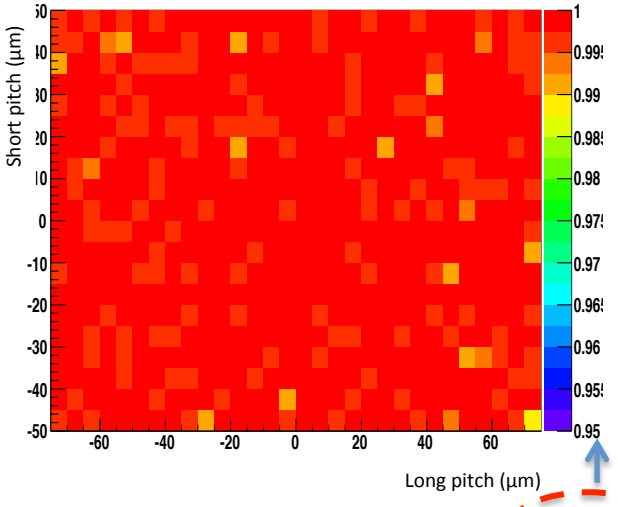
Prototype 56D-3E @ 30V
Orthogonal tracks



Detector 5 degree tilted



Detector 10 degree tilted

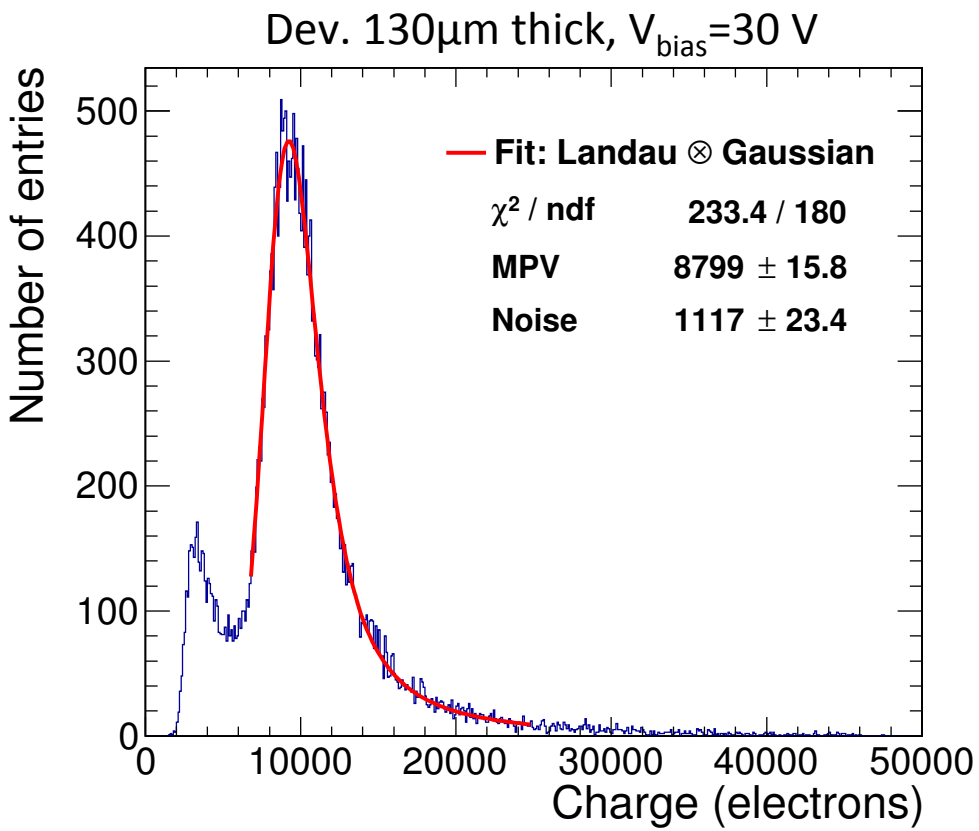


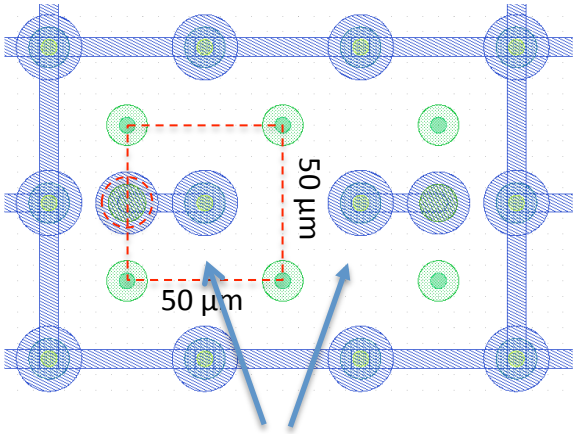
Angle (degrees)	*Efficiency 3E*	*Efficiency 2E*
0	**99.27%**	**99.45%**
5	**99.77%**	**99.85%**
10	**99.88%**	**99.87%**
max Δ Efficiency	**0.62%**	**0.43%**

- Efficiency improved for non orthogonal tracks

- Almost full geometrical factor recovered
  - 3E Detector Efficiency by +0.6%
    - Fraction of column area ~0.8%
  - 2E Detector Efficiency by +0.4%
    - Fraction of column area ~0.5%

Beam test Small pitch 3D Pixel: 50 x 50 μm²



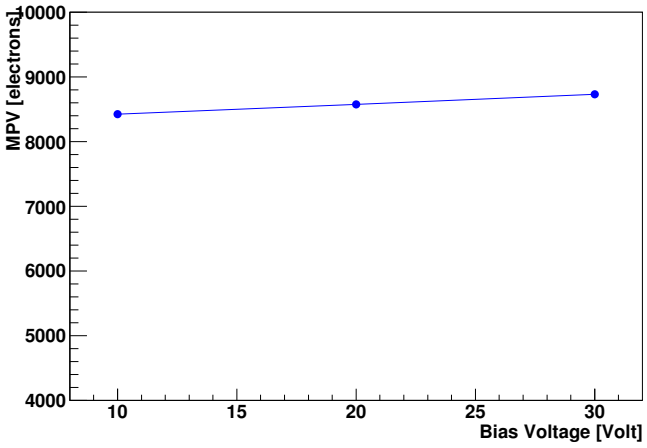


Two adjacent double columns pixel readout ROC (PSI46dig) fully connected

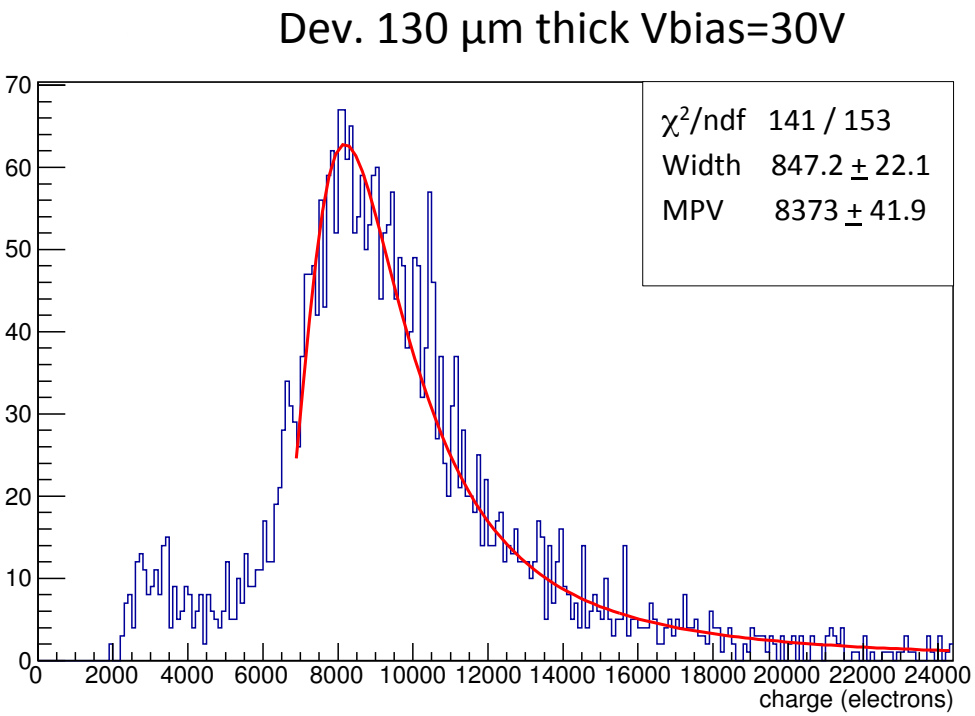
Sensitive area readout: 1/6

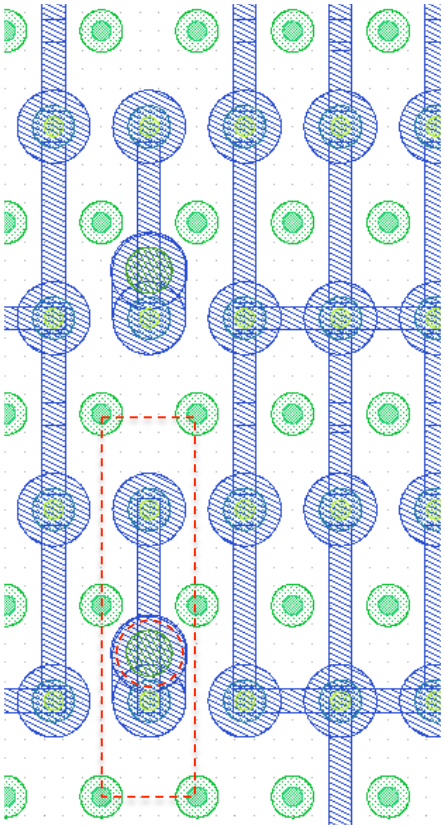
Charge shared with not readout adjacent pixels. Effect over 3/4 cell sides

MPV vs Bias Voltage



Beam test Small pitch 3D Pixel: 25 x 100 μm²





Charge shared with not readout adjacent pixels. Effect over 2(long)/4 cell sides

One full column readout
ROC (PSI46dig) fully connected
Sensitive area readout: 1/6

Conclusion

- R&D programs to develop thin, radiation tolerant, fine pitch sensors and address pixel design/assembly issues
  - A few research programs on going in parallel within CMS
    - Planar: CMS/HPK submission, INFN/FBK (together with ATLAS)
    - 3D: INFN/FBK (together with ATLAS), CNM
  - Design and Radiation hardness study
    - Efficient and precise tracking at high rates
    - Material, Pixel Bias scheme, ...
  - Prototype assembly: fine pitch bump bonding of thin sensors/ROCs challenging and a major cost driver for small pitch

- Preliminary results on prototype show good data quality for planar and on 3D pixels, detailed analysis on smallest pitch devices still ongoing
  - Thin 3D pixels, n-in-p, are working as expected, both for standard pitch and new 50x50 μm^2 25x100 μm^2pitch (preliminary results)
  - Qualification and Irradiations campaign to be completed
    - Today constraint from PSI46dig ROC performance
  - New Beam test experiments planned in order to fulfill this program

- Activity on going: new wafers submission at process or qualification step
  - New ROC (PROC600, RD53, ROC4sens,..) for Phase-2 pitch pixel assembly.

Back Up

Tracker radiation dose

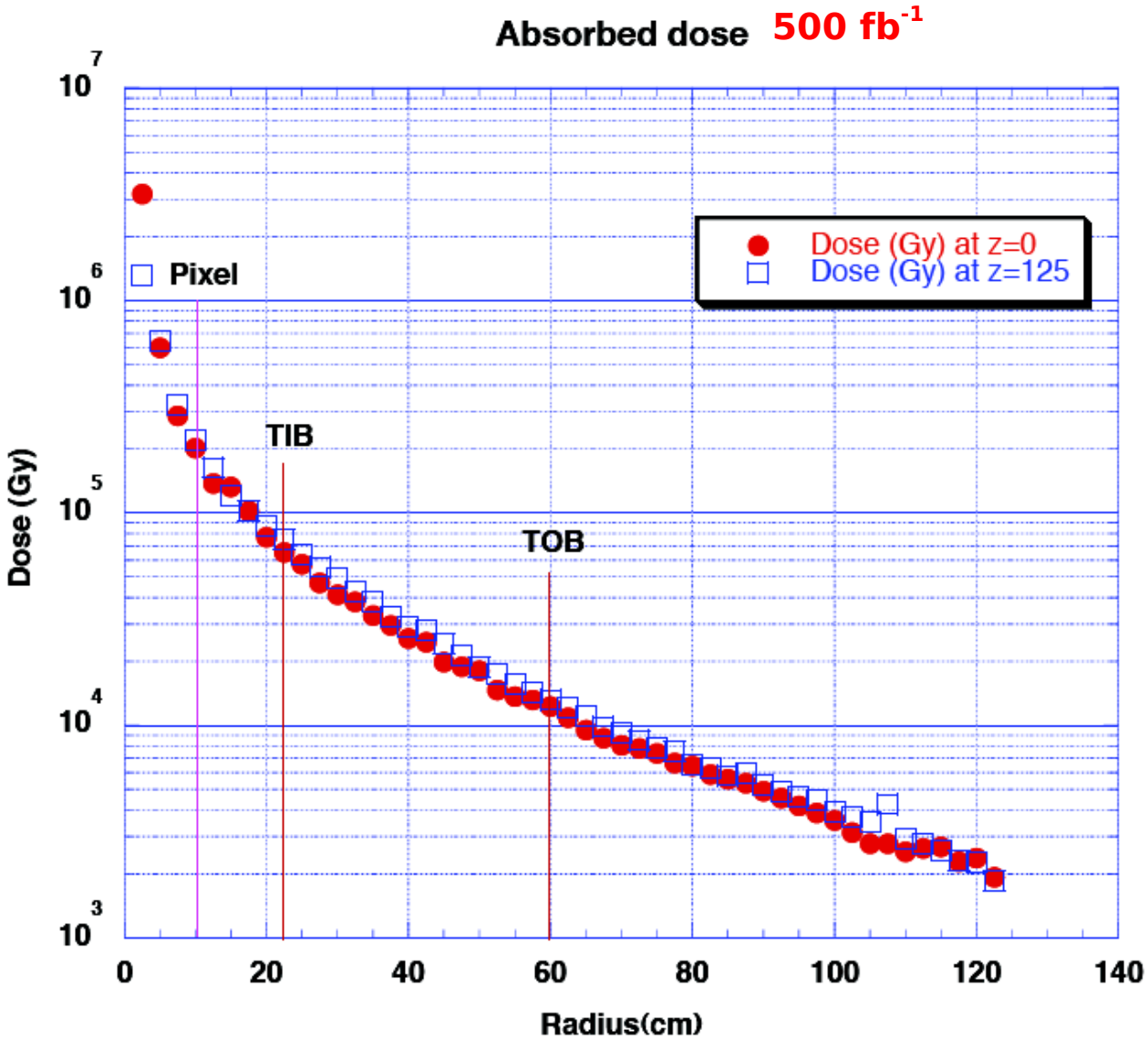
1 Gy = 100 Rad

Layer 1: 100 MRad

Layer 2: 40 MRad

Layer 3: 20 MRad

Layer 4: 13 MRad



Fluence:

1 MRad ≃ 3 10^{13}/cm^2 pions

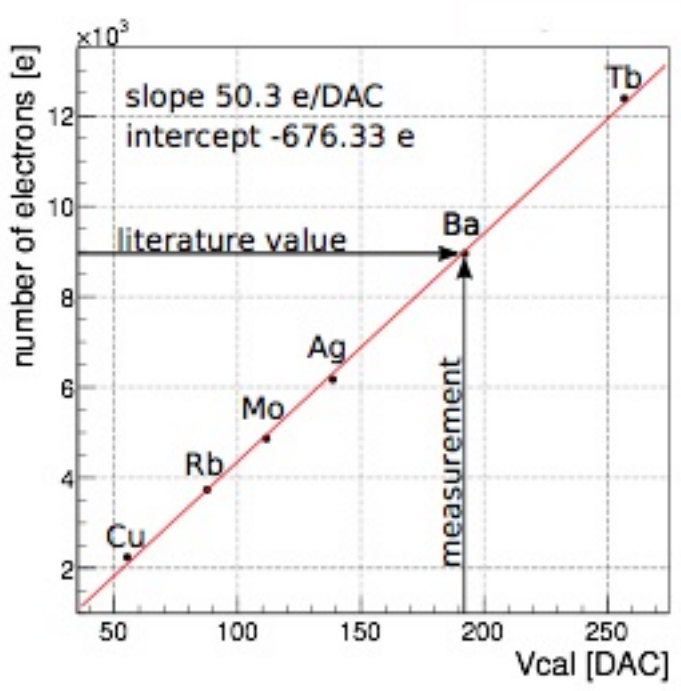
Pixel upgrade TDR 2012

Psi46dig

- Threshold : in time 1800-2000 e The difference, ΔQ, between absolute and in-time threshold 100-200 e

- Radiation hardness
- Desy dice soglia 1.8 ke

Table 4.1: List of the applied target materials presenting their K_α transition energies as well as the expected number of electrons N_{el} created via the photoelectric effect [NIS13].



Target	E_{K_α} [eV]	N_{el}
Fe	6403.13	1779
Cu	8048.11	2236
Zn	8639.10	2400
Rb	13 395.05	3721
Mo	17 479.10	4855
Ag	22 162.99	6156
In	24 209.78	6725
Sn	25 271.34	7020
Ba	32 192.87	8942
Nd	37 361.40	10 378
Tb	44 485.90	12 356

Radiation hardness

CMS

- Sensors are used for the present BPIX.
- Performance fully satisfactory
- Radiation level is still low but above the point of space charge sign ("type") inversion

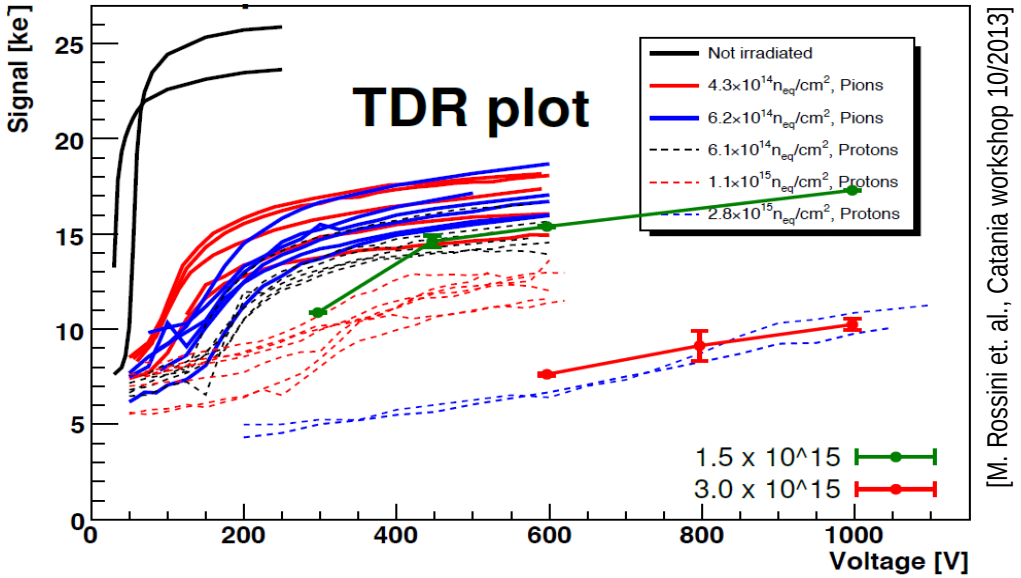
Radiation hardness studies

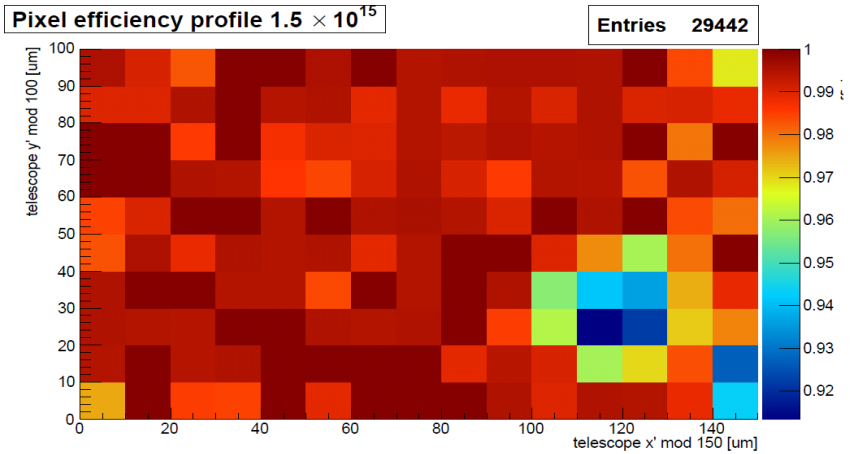
- ~1.2×10^{15}N$_{eq}$/cm^{-2}:

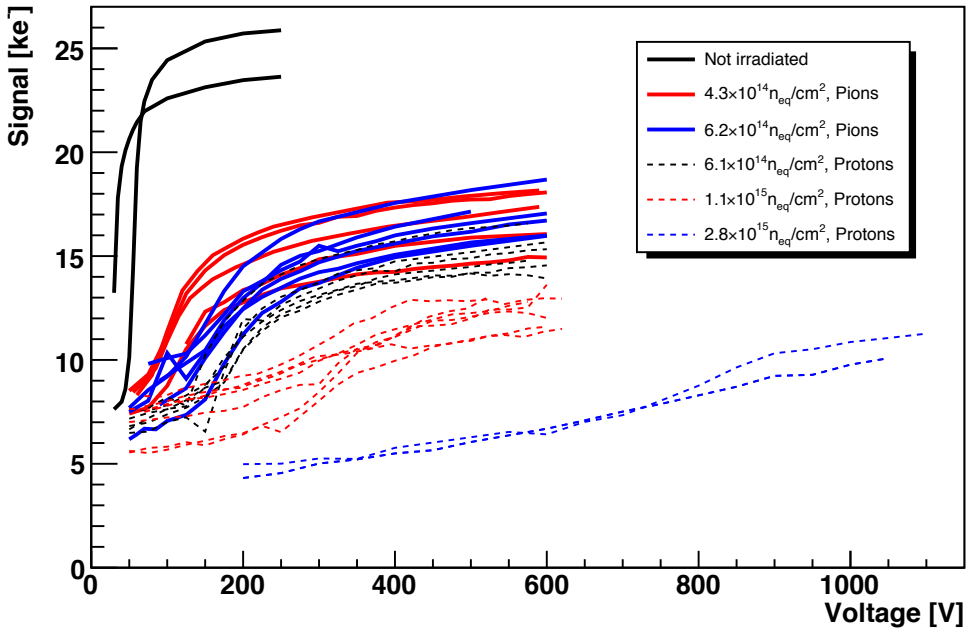
  Several test beam studies in the years 2002-06
  NIM A 583 (2008) 25-41
- **Summer 2013: 1.5 and 3×10^{15}N$_{eq}$/cm^{-2}**

  Irradiation at KIT and testbeam at DESY

Signal height and detection efficiency fully sufficient for the targeted radiation level of 1.5×10^{15}N$_{eq}$/cm^{-2} (~250fb^{-1} in layer 1 at 3cm)







pixel-phase-ii-PSI

Figure 6.4: Charge collection in non-irradiated and irradiated sensors with different doses and different particle types (sensors of 285±15 μm thickness.)

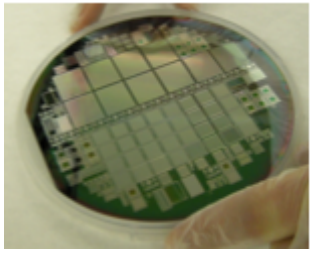
PSI46dig digital version:

Charge threshold:	>1.5ke-
Charge resolution:	~120e-
(pixel-by-pixel calibration needed)	
Rad hardness:	>250 Mrad
Operation:	triggered only

Material

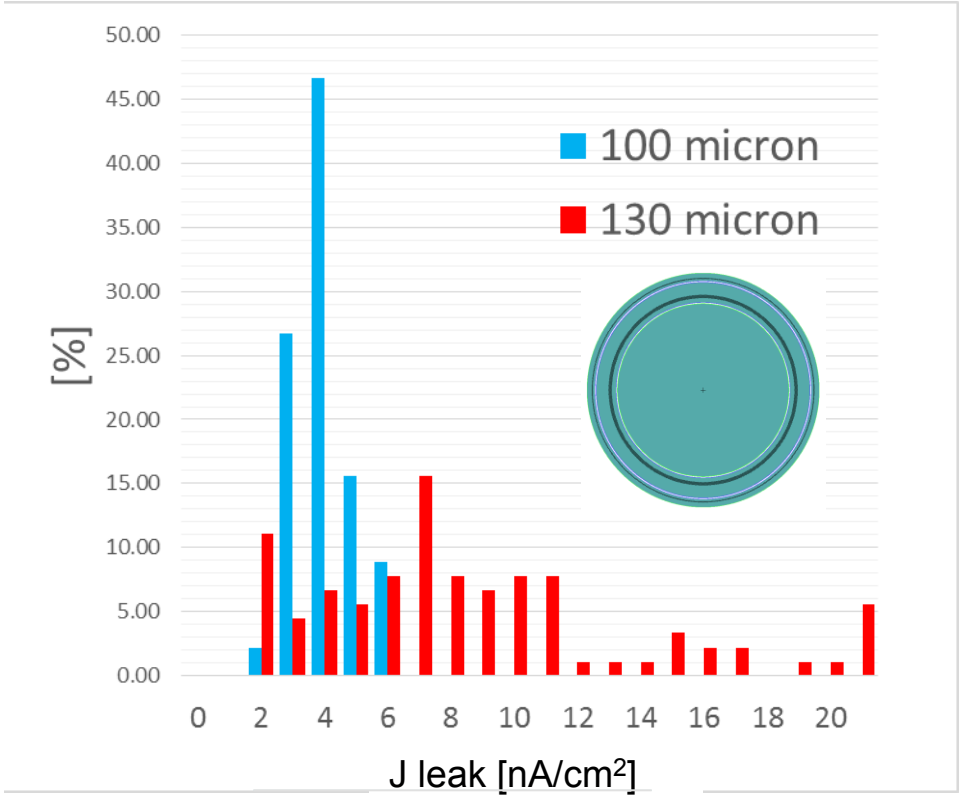
SiSi DWB substrate qualification

Planar sensor test batch, 2014



G.-F. Dalla Betta, NIMA 824 (2016) 388

Circular diode, 4 mm^2, two GRs

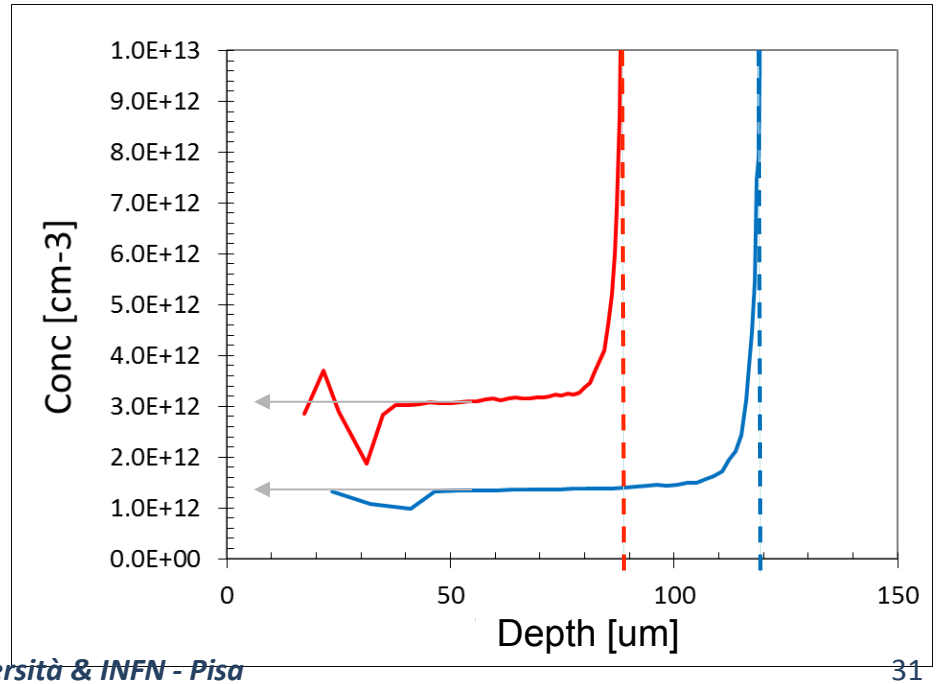


J_{leak} distribution on 135 diodes

→Different material quality ?

Doping concentration profiles:

- Active layer doping 1 – 3 x 10^{12} cm^{-3}
- Thicknesses about 10 μm lower than the nominal values, due to Boron diffusion from support wafer



Test diode: C-V measurements

Measured at FBK

Depletion voltages:

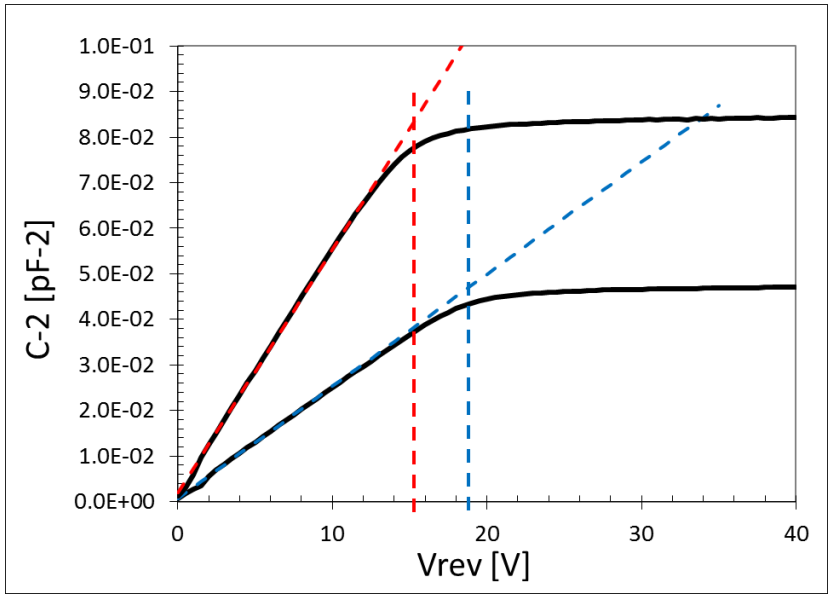
- V_{depl} ~ 16V for 100 μm thick.
- V_{depl} ~ 20V for 130 μm thick.

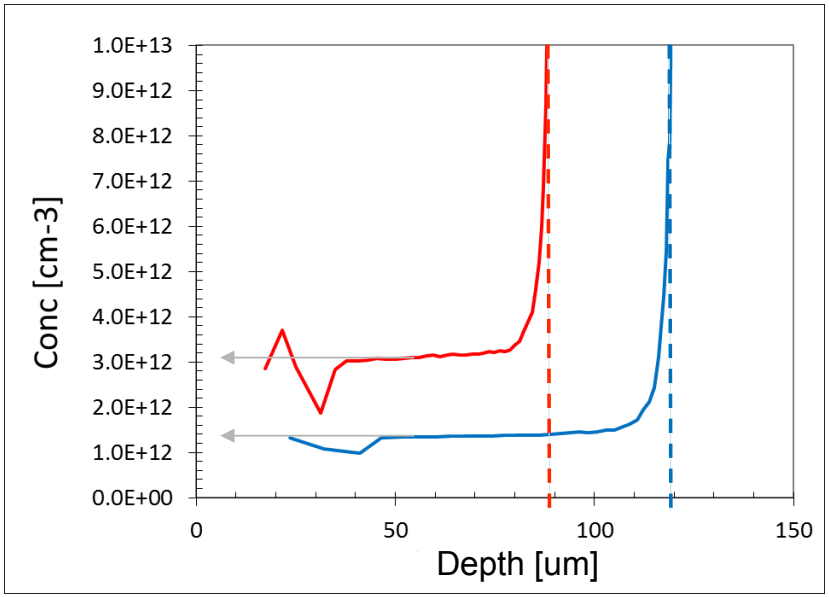
do not scale with square of thickness

→ Different resistivities …

Concentration profiles

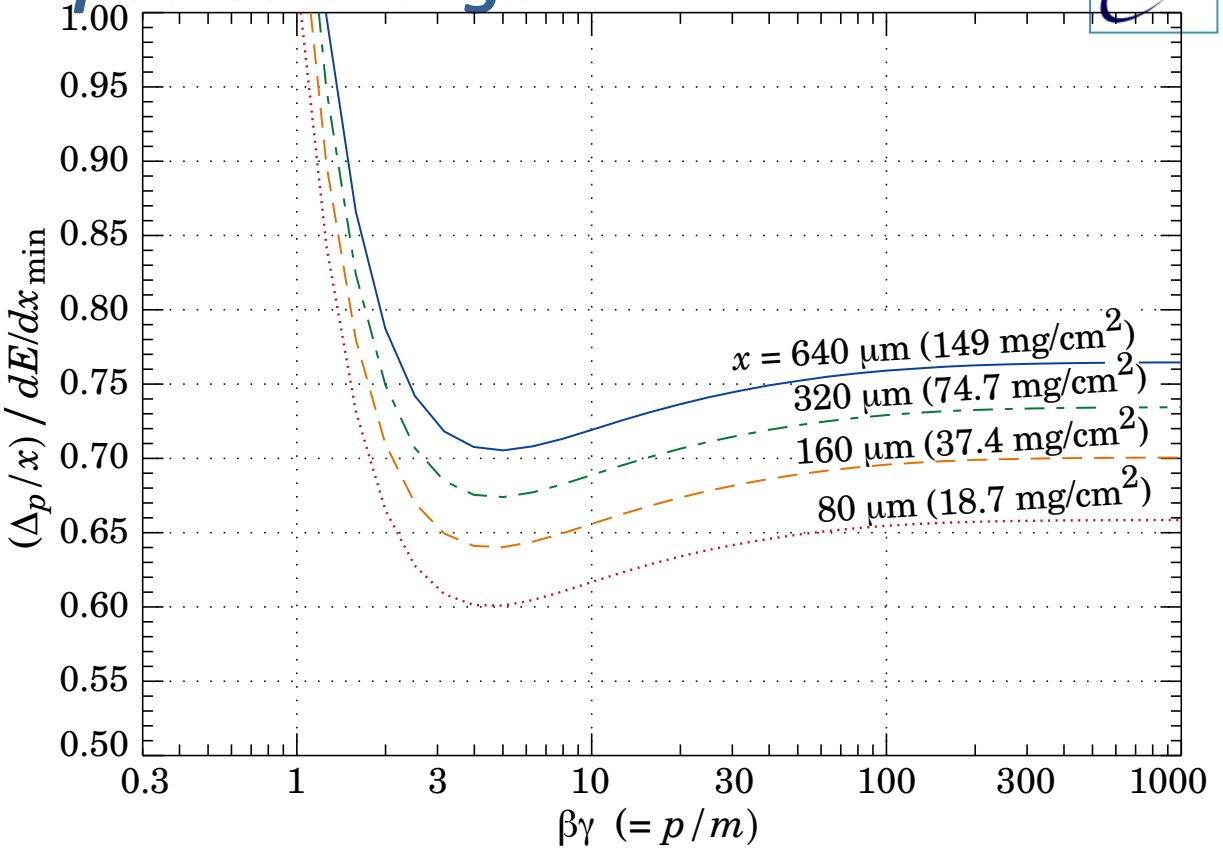
- Doping 1 – 3 x 10^{12} cm^{-3}
- Thicknesses about 10 μm lower than the nominal values, compatible with Boron diffusion from support wafer and measurement limit (L_{debye})





Expected charge

Theory Deltap/micron	spessore (micron)	
232.8	160	
252.2	80	
threshold eV/pair	100 um	130 um
3.6	6467	8407
2.3	10122	13158
75 e-h/micron?		
75	7500	9750

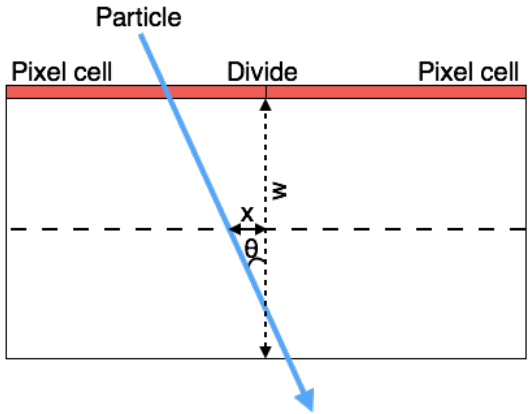


31.9: Most probable energy loss in silicon, scaled to the mean l ionizing particle, 388 eV/μm (1.66 MeV g^{-1}cm^2).

Beam test: charge sharing neighboring pixels

- *Charge collected proportional to "on pixel" projected track length*
  - $w/2 \bullet \tan(\theta) + x \sim charge_L$
  - $w/2 \bullet \tan(\theta) - x \sim charge_R$

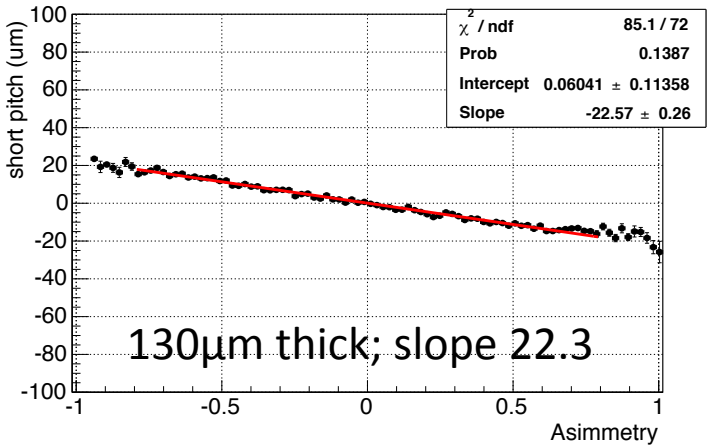
$$Asymmetry = \frac{charge_L - charge_R}{charge_L + charge_R}$$

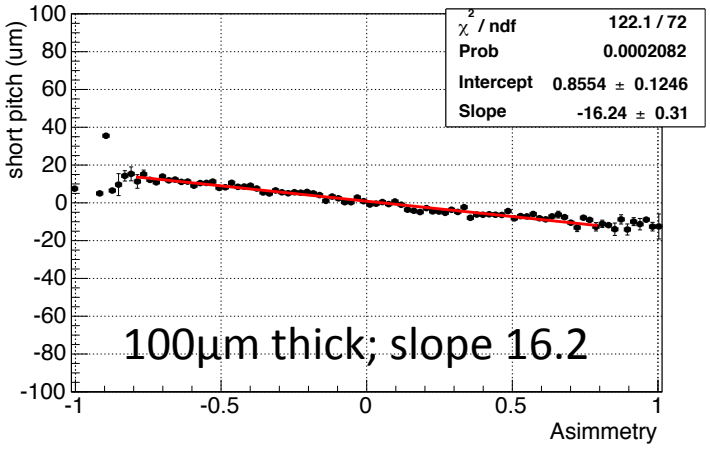


- $Asymmetry = 2x / (w \bullet \tan(\theta))$
- **Slope** = x/Asymmetry = $w/2 \bullet \tan(\theta)$

w = 100 µm ➜ Slope = 18.2 µm/asymmetry
w = 130 µm ➜ Slope = 23.7 µm/asymmetry

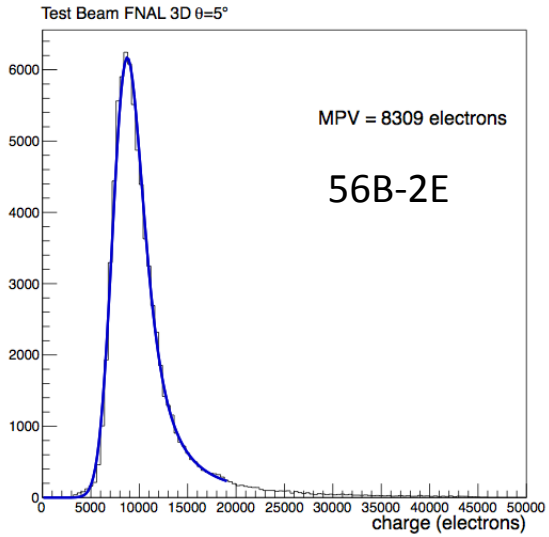
- **Standard** Pixel prototype

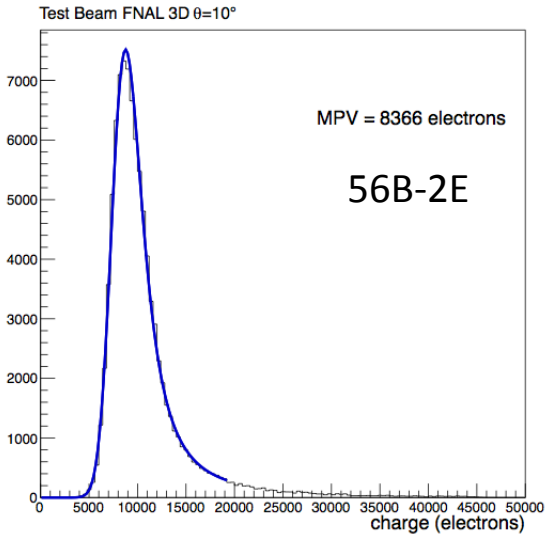




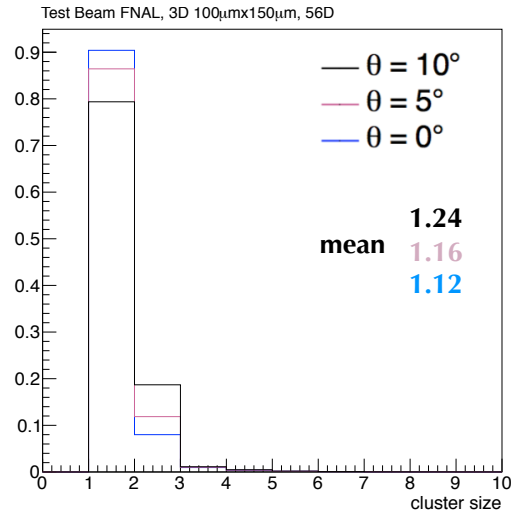
Charge and Cluster width: tilted

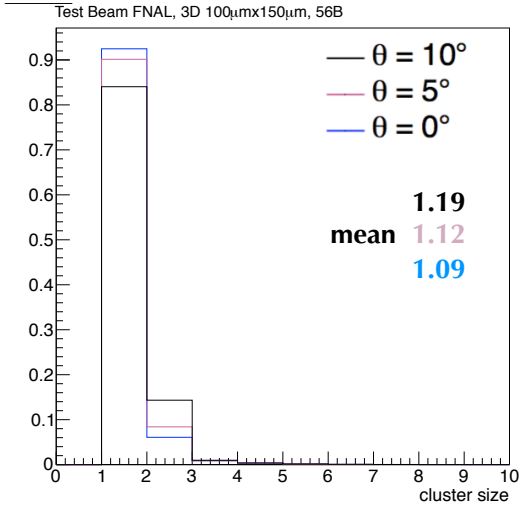
- Charge increases (~0.6%) with track angle and track length

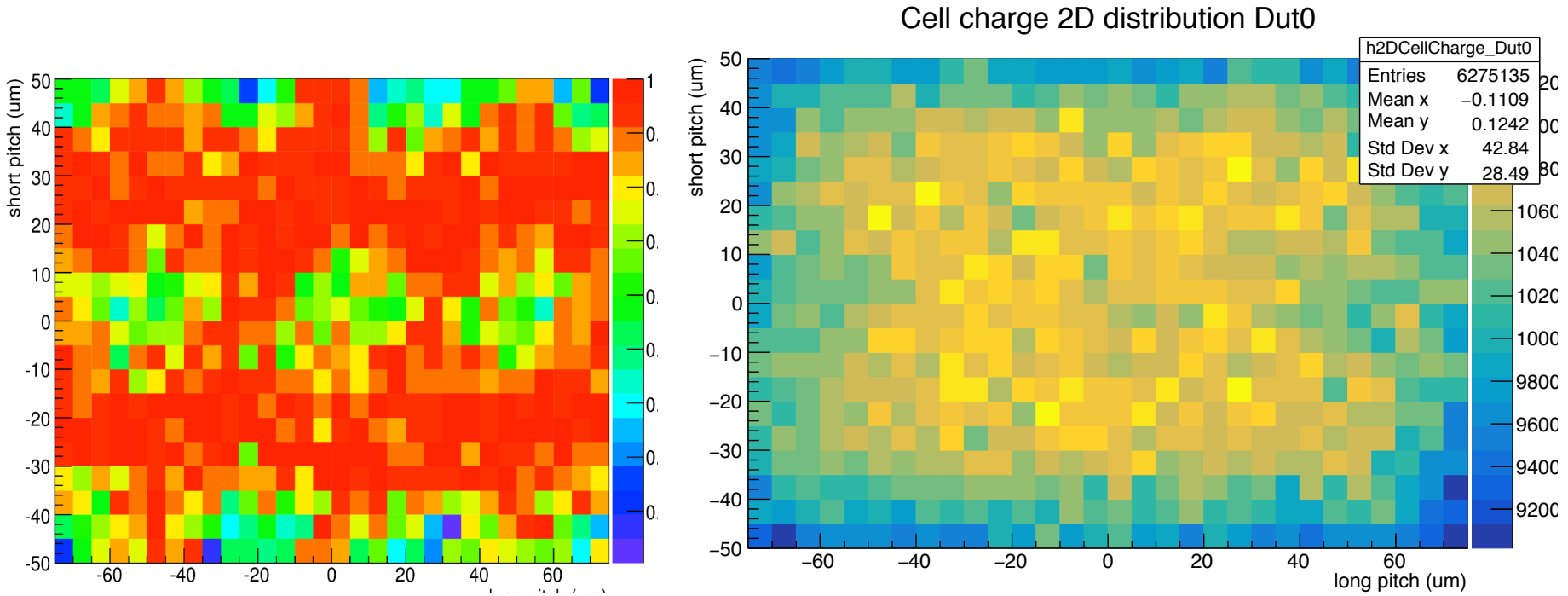




- Cluster width increases by ~10% for 2E and 3E





56B - 2E **56D - 3E**

- Efficiency is high: charge collected is far beyond the measurement threshold