Pixel Detector Developments for Tracker Upgrades of the High Luminosity LHC

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on behalf of CMS and Pixel R&D INFN Collaboration

International Conference on Technology and Instrumentation in Particle Physics 2017

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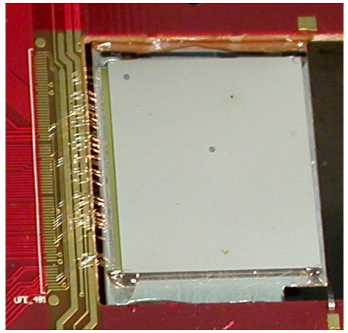
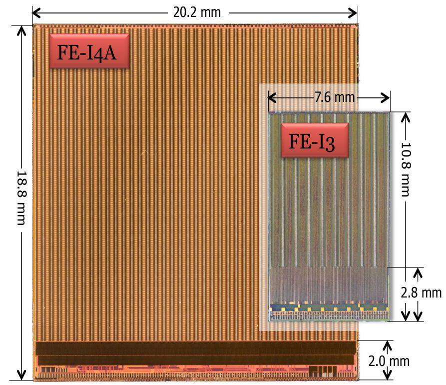
Overview of the R&D Program

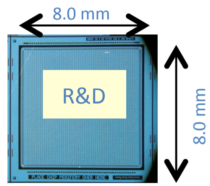
- The INFN Pixel R&D Program for HL-LHC
  - A four year program on 3D and Planar Pixel Sensors funded by INFN and FBK (Italy) under special agreement
    - Common project originating from CMS and ATLAS researchers in Italy
- **Scientific objectives:**
  - **3D and Planar** small thickness pixel sensors, to be used in the inner layers of future trackers at High Luminosity LHC
  - Technology and design optimized and for **high radiation hardness** on p-type 6” wafers, 100 and 130µm active thickness
    - CMS inner layer: **~ 2.3x10^{16} neq cm^{-2}** fluence and **~ 1.2 MGy** dose
  - Small pitch pixels: layouts **compatible with present ROCs and prototype (as RD53A in 65nm) FE chips**
  - **Sensor features**: spark isolation techniques, different active and handle wafers options, thinning, high density bump-bonding
- **Performance of Planar and 3D pixel sensors on Beam Test**
- **Strong synergy with WP7 (Advanced Hybrid Pixel Detectors) in EU R&D programme AIDA-2020**

ATLAS Pixel on a FE-I4 chip

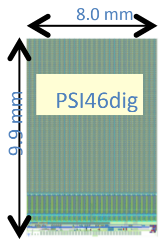


Present ATLAS and CMS FE chips





R&D n-in-p Pixel Sensor



CMS digital FE chip

INFN-FBK Pixel R&D Project

- **Two pixel technologies for n-in-p wafers:**
  - Planar
    - Process Options: p-spray on wafer and/or p-stop around single pixel
    - Periphery design: standard and Active or Slim-Edge (special planar batches), multi Guard Rings
  - 3D Columnar
    - Single Sided processing optimized by FBK for different active thicknesses
    - Process options: bump on columns, poly-silicon ”cap” on top of junction columns
- **Productions, Achievements and Plans**
  - Two Planar and one 3D columnar pixel batches produced so far at FBK premises
  - Prototypes qualified in laboratory and in multiple beam test sessions 2015-2017
  - One neutron and two proton irradiation sessions done in 2016, two more to come in 2017
  - One new3D pixel batch in production now at FBK under AIDA-2020 WP7 agreement
  - One more Active/ Slim-Edge pixel batch agreed with AIDA-2020 to be started as soon layout is ready

R&D Working Groups in INFN and Universities: a long list of highly skilled people

Design, processing, qualification, assembly

M. Boscardin, G. Giacomini[1], S. Ronchin , N. Zorzi (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, D. Menasce, L. Moroni, D. Zuolo (Milano)
C. Civinini, M. Meschini, G. Sguazzoni L. Viliani, I. Zoi[2] (Firenze)
L. Uplegger, R. Rivera, C. Vernieri (FNAL, USA)

[2] Now at Hamburg Univ.

First Planar Batch Layout

Active Device 6” Float Zone Si-Si DWB (Direct Wafer Bond, Icemos), P type, FZ Sensor resistivity > 3kOhm cm, 100μm and 130μm thick. CZ Handle wafer, 0.1-1 Ohm cm resistivity, 500μm thick

All **planar pixel** results shown today are obtained from sensors of this production

FBK production 9 DWB wafers:
6 x 130μm + 3 x 100μm

FBK QA test structures

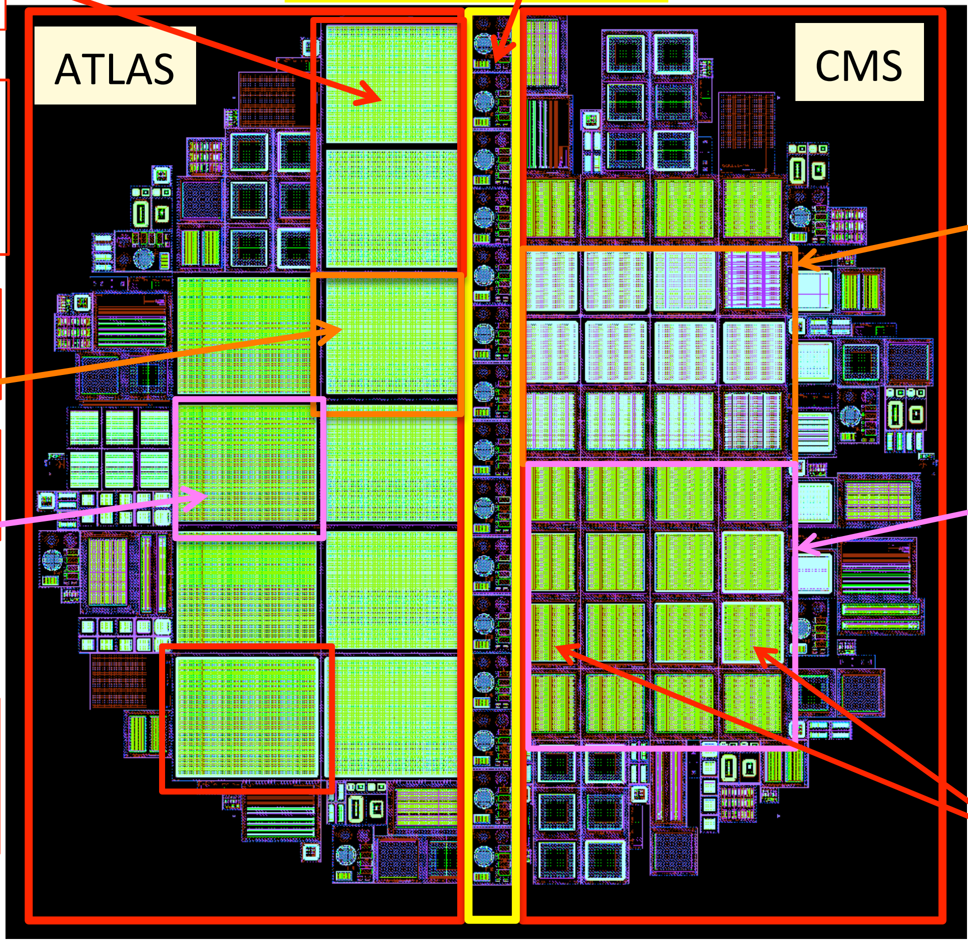
ATLAS Double (FE-I4)

Increasing number of Guard Rings from row 4 to 1

Standard Punch Through

New Punch Through

8 ATLAS single sensors (FE-I4) total



Similar wafers used for planar, 3D, AE batches

Pixels with P_stop

32 CMS (PSIdig) total

Pixels without P_stop

Increasing number of Guard Rings from col. 1 to 4

P-spray in 3 doses (Low-Med-Hi)

Layout finalization at FBK: G. Giacomini, M. Boscardini, N. Zorzi

Planar Pixel Sensor Design

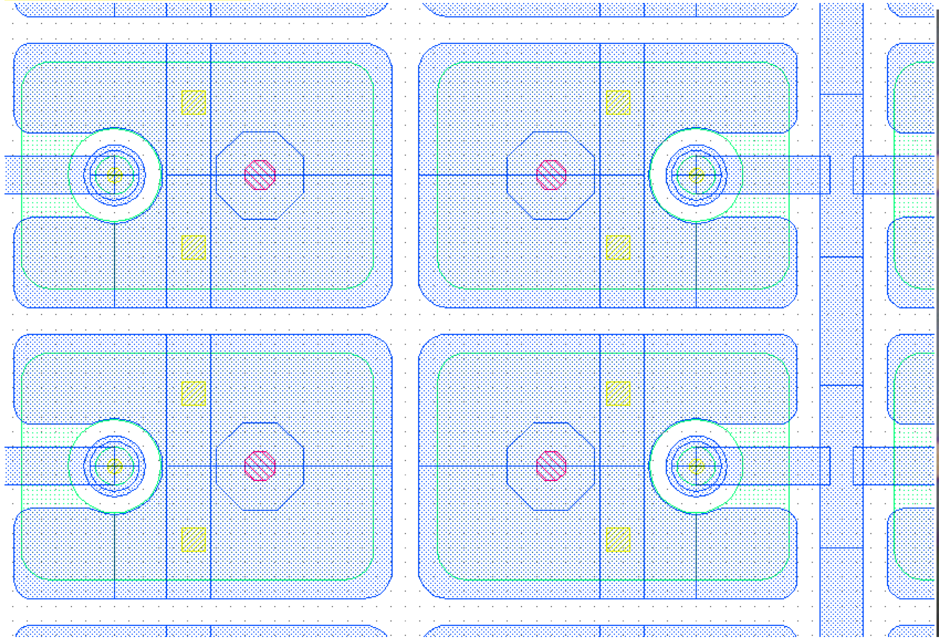
Picture and gds layout of a standard CMS sensor

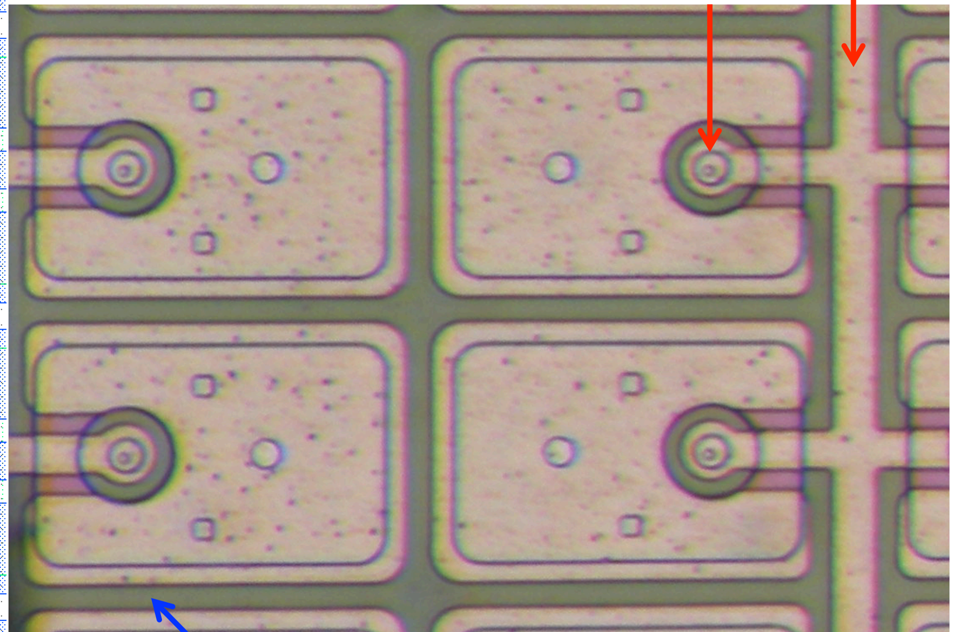
Metal Bias Grid

Design layout

Optical microscope picture

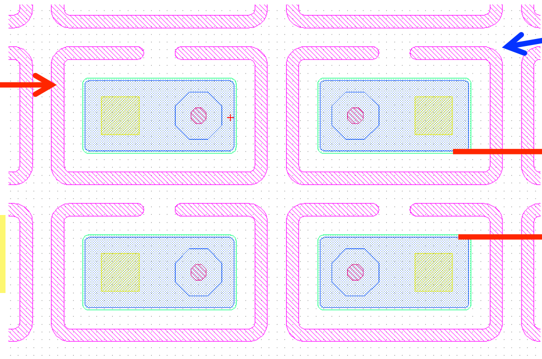
Punch Through





Pixel size 100µm x 150µm

P-stop

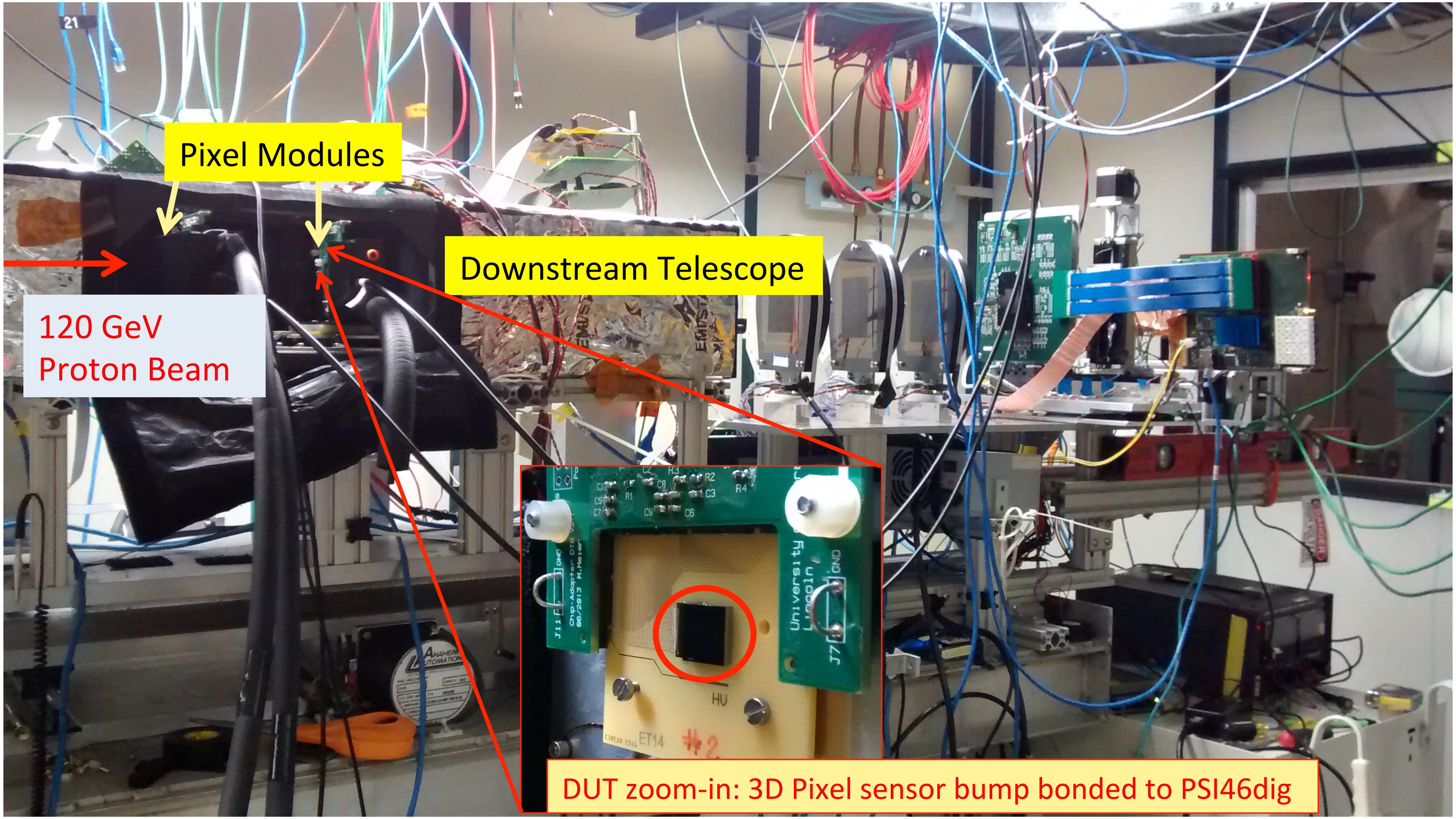


50µm gap between n$^+$ implants, extreme case
Usually 20-30µm gap

No PT pixel design layout

Test Beam Setup for Pixel Detectors at Fermilab

The Fermilab pixel telescope: described in detail *NIM-A 811 (2016) 162-169*
Main features: 8 pixel planes based on PSI46 analog chip (100x150 μm^2 pixel cell), ~8 μm resolution



Radiation damage: first planar pixels irradiated at Los Alamos

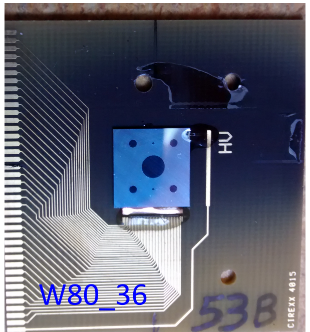
Standard pixel prototype 100x150 μm^2

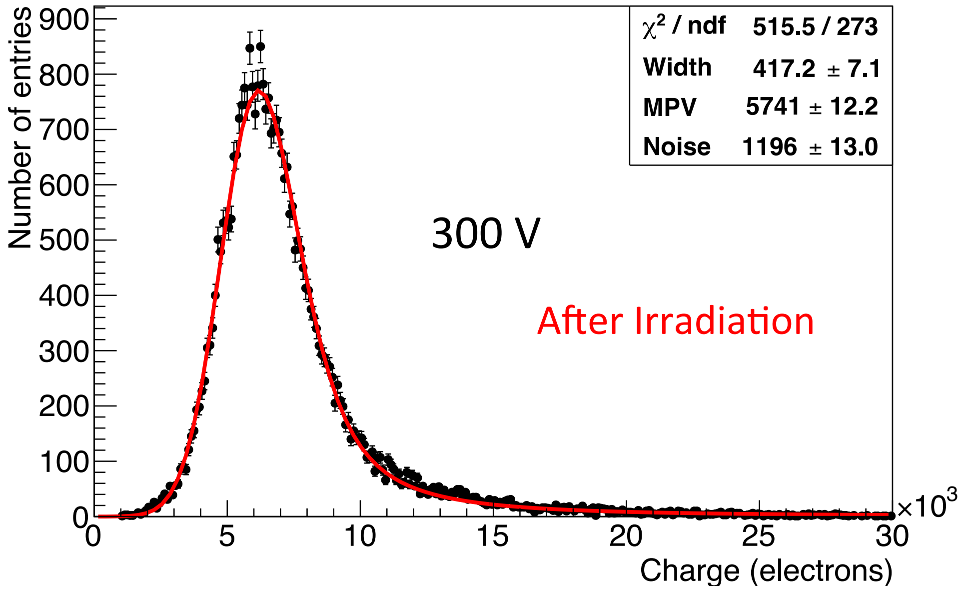
- 130 μm active thickness, 285 μm in total

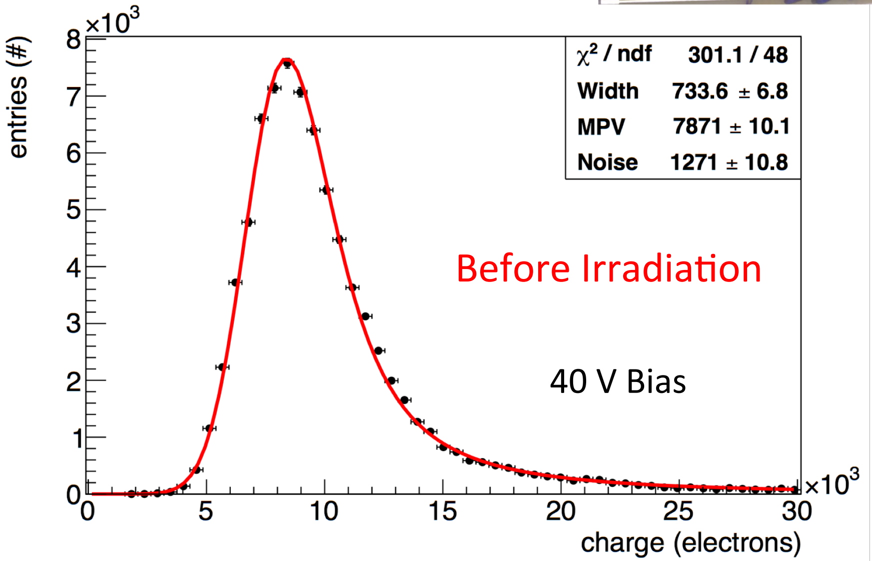
Proton irradiation at Los Alamos LANSCE

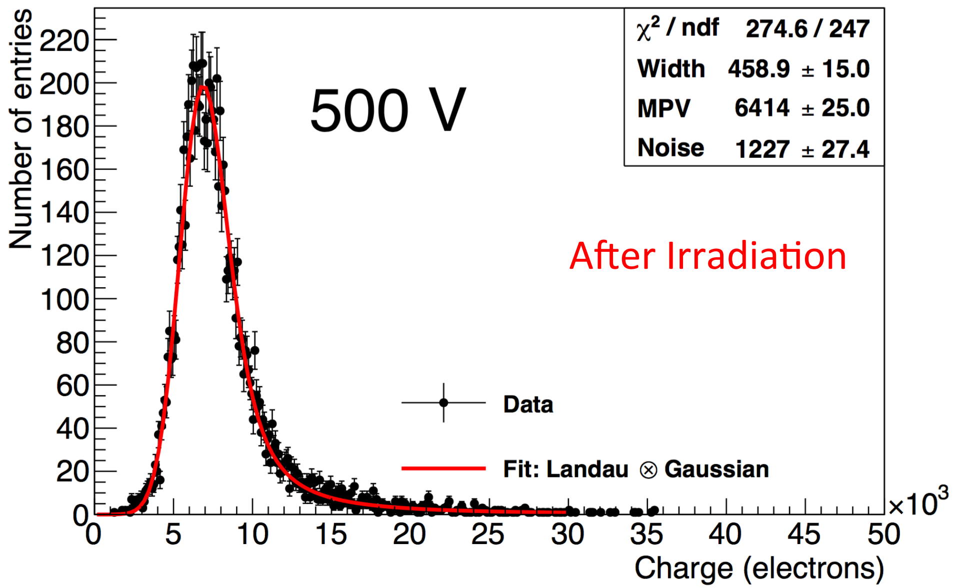
- **1.2×10^{15} n_{eq} cm^{-2}**
- ~20 % of charge loss observed at 500V w.r.t. non irradiated module

800MeV proton Beam Halo clearly visible on module PCB
Irradiation not uniform over the module









Irradiation of Planar Modules at CERN

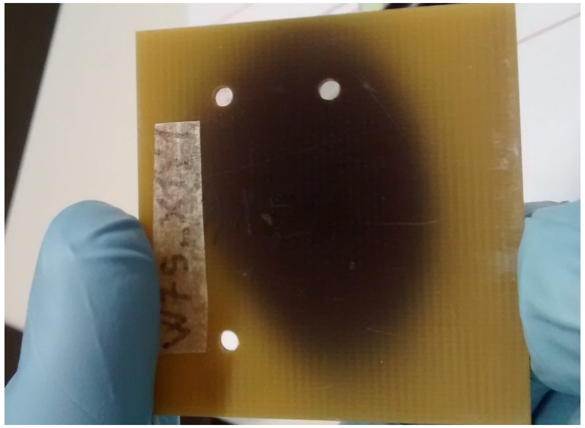
Samples ready for shipping to CERN IRRAD

24GeV Protons @ CERN

All the modules to be irradiated were previously tested on beam at FTBF FNAL in Dec 2015 or May 2016

The PSI46dig is the same ROC of CMS Phase1 new pixel tracker for layers 2-4

3, 5 and 7x10^{15} neq cm^{-2} average fluences



Rack with modules on IRRAD beam-line

Modules on the IRRAD beam are installed back-to-back in pairs

Irradiations performed thanks to F. Ravotti and G. Pezzullo CERN

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 654168.

Test Beam Results on Proton Irradiated Planar Modules

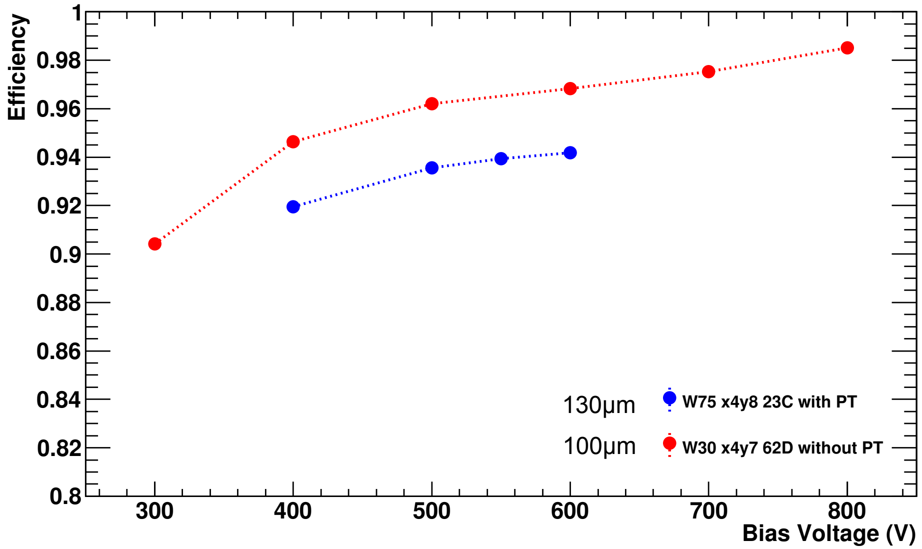
- Two planar hybrid modules (100µm and 130µm thickness) irradiated to 3 E15 neq/cm^2 (5.2 E15 24GeV protons/cm^2) with PSI46dig ROC were tested on February 2017 TB @FNAL
- At this fluence we are already close the the maximum radiation dose the PSI46dig can reach and still be functional: we see some losses in the charge distribution
- One module has a Punch Through bias structure on each pixel
- One module has no PT, C-shape P-Stop, and it has a very large (50µm) gap between pixel implants
- Modules have two BCB (Benzocyclobutene) protective layers: one on the pixel sensor and one on the PSI46dig → HV up to 800V (600V) without problems

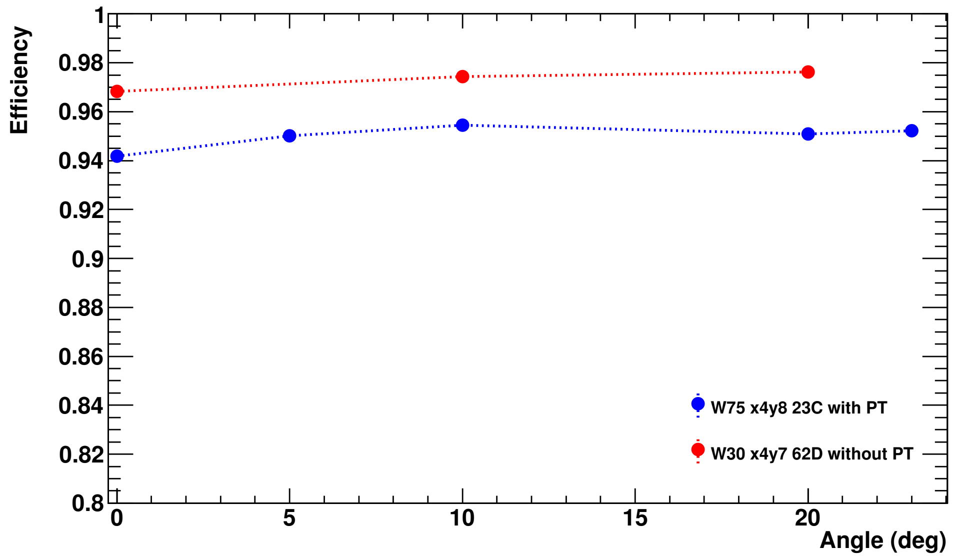
Average Irradiation fluence **3 x 10^{15} neq/cm^2**

Global Efficiency vs V_Bias

Planar Pixel

Global Efficiency vs Track Angle, 600V Bias

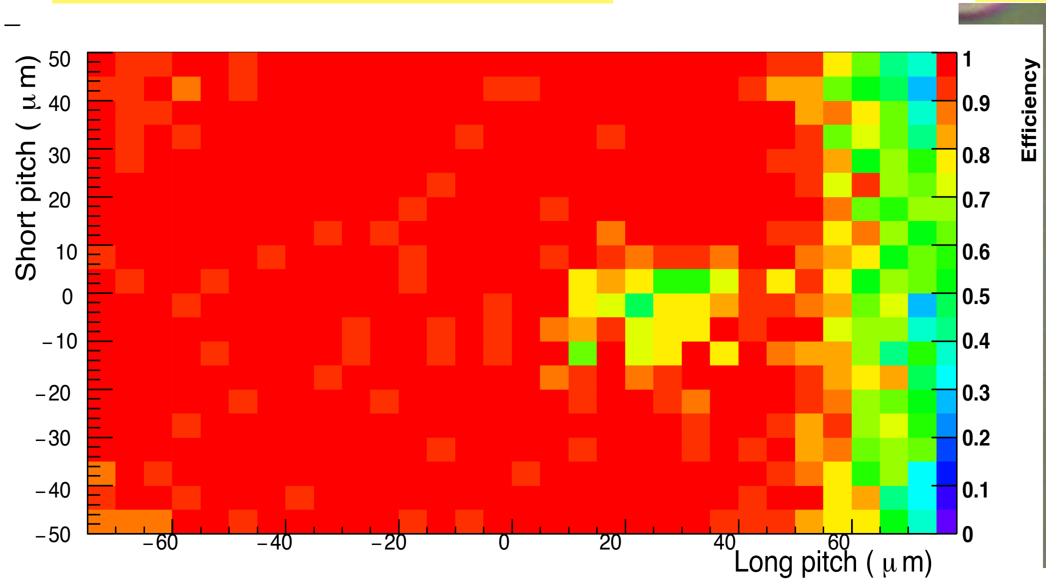




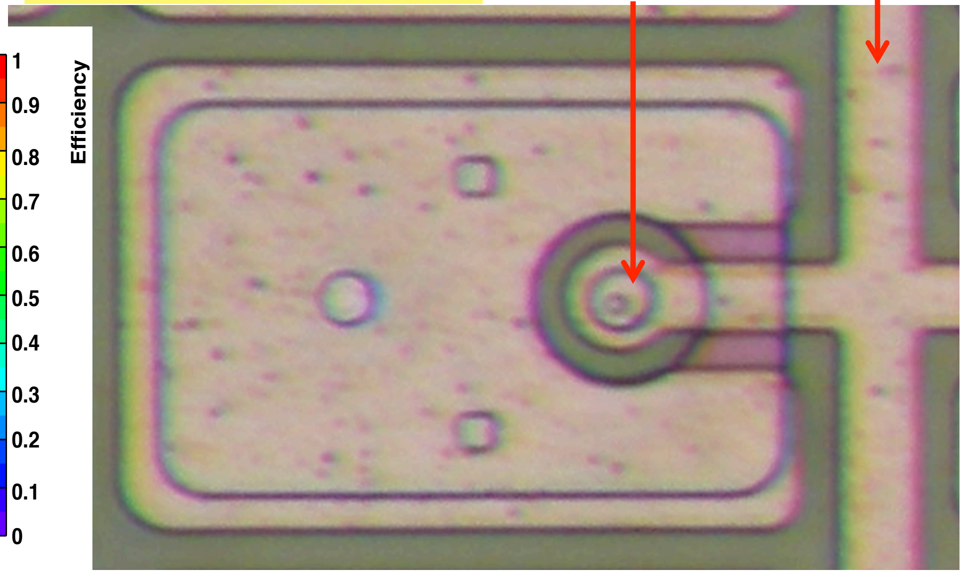
Planar Pixel with Punch Through Bias Grid

Efficiency of the the proton irradiated module and picture of the sensor

Cell efficiency at 400V bias



Optical microscope picture



The effect of the bias grid and Punch Through is visible with orthogonal tracks at 400V bias
Efficiency recovered for inclined tracks at ~10 degrees angle
Efficiency saturation value is 0.95 averaged over all the sensor

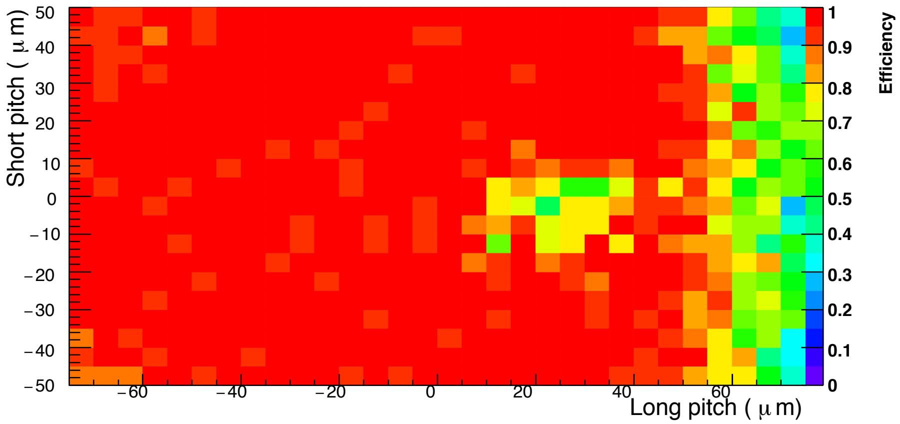
Punch Through Pixel Sensor Efficiency vs Vbias 400-600V

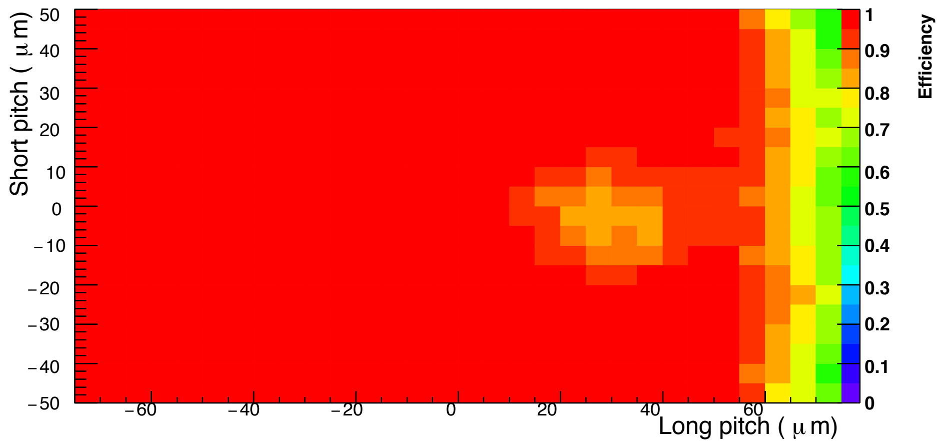
Proton irradiated at 3E15 neq/cm2

400 V bias

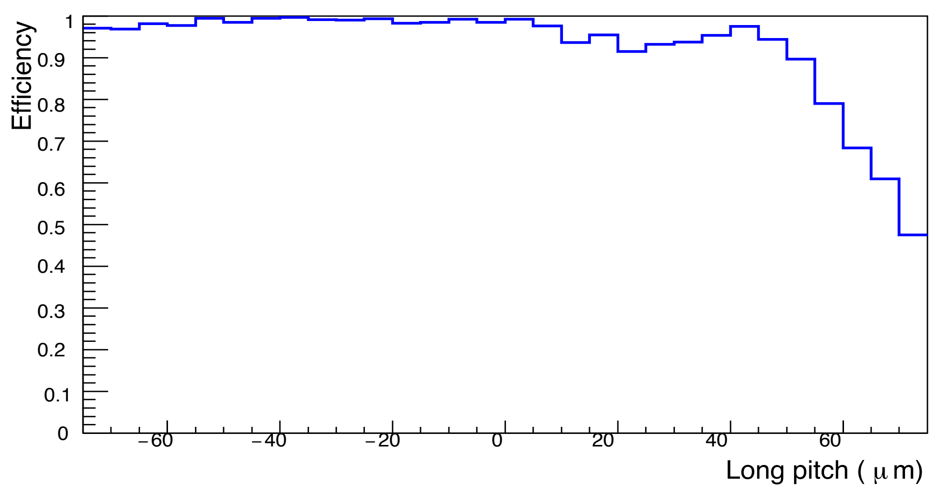
Cell efficiency

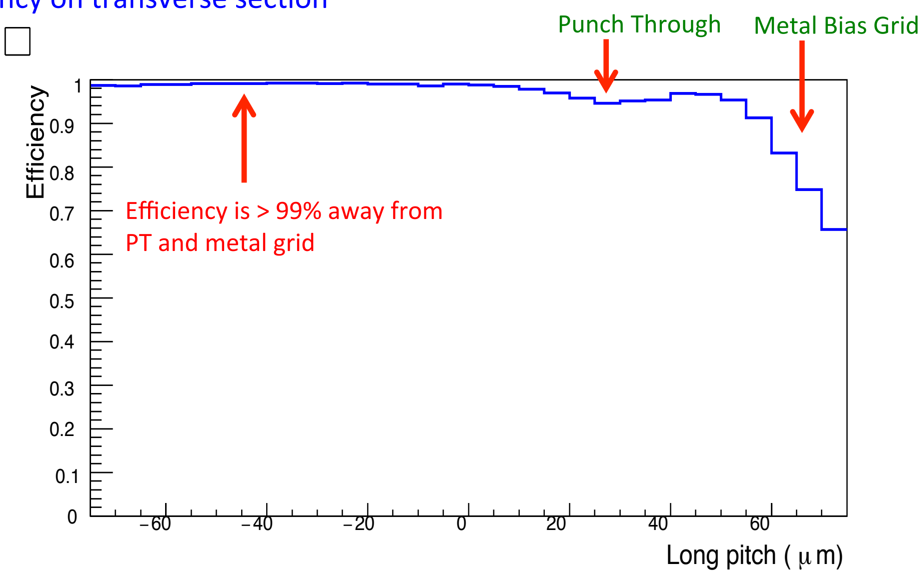
600 V bias





Projected efficiency on transverse section

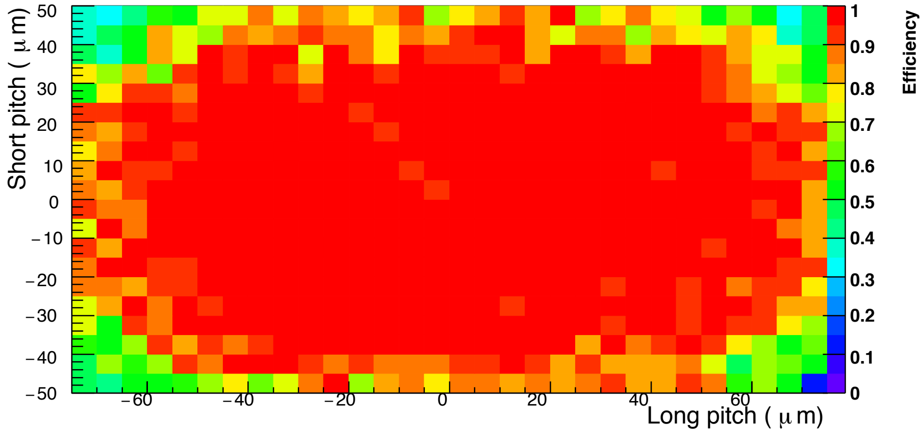




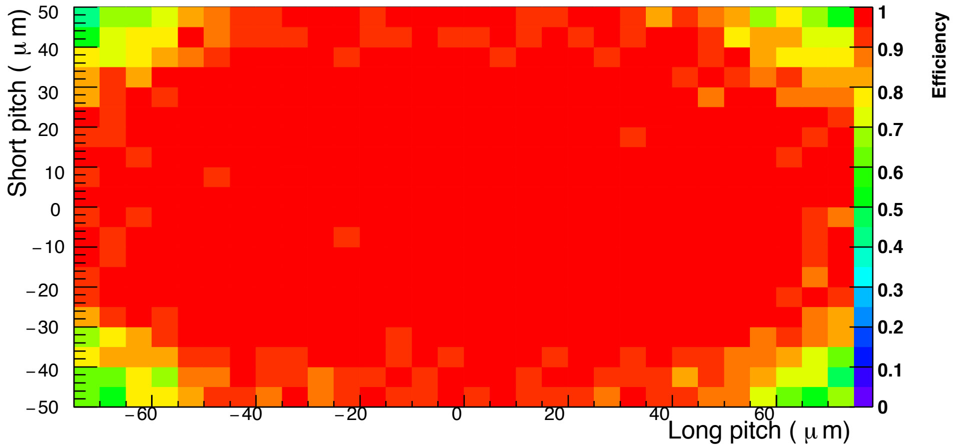
Pixel Efficiency vs Vbias 300-800V (No Punch Through Pixel)

Proton irradiated at 3E15 neq/cm2

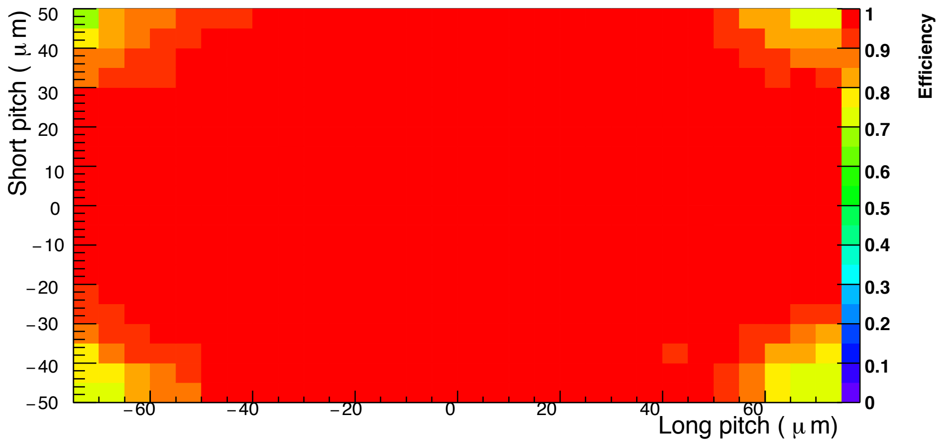
300 V bias



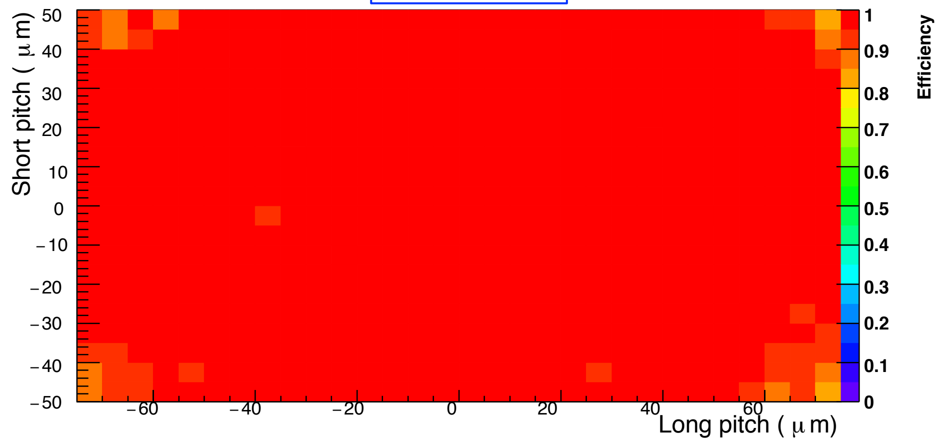
400 V bias



600 V bias



800 V bias

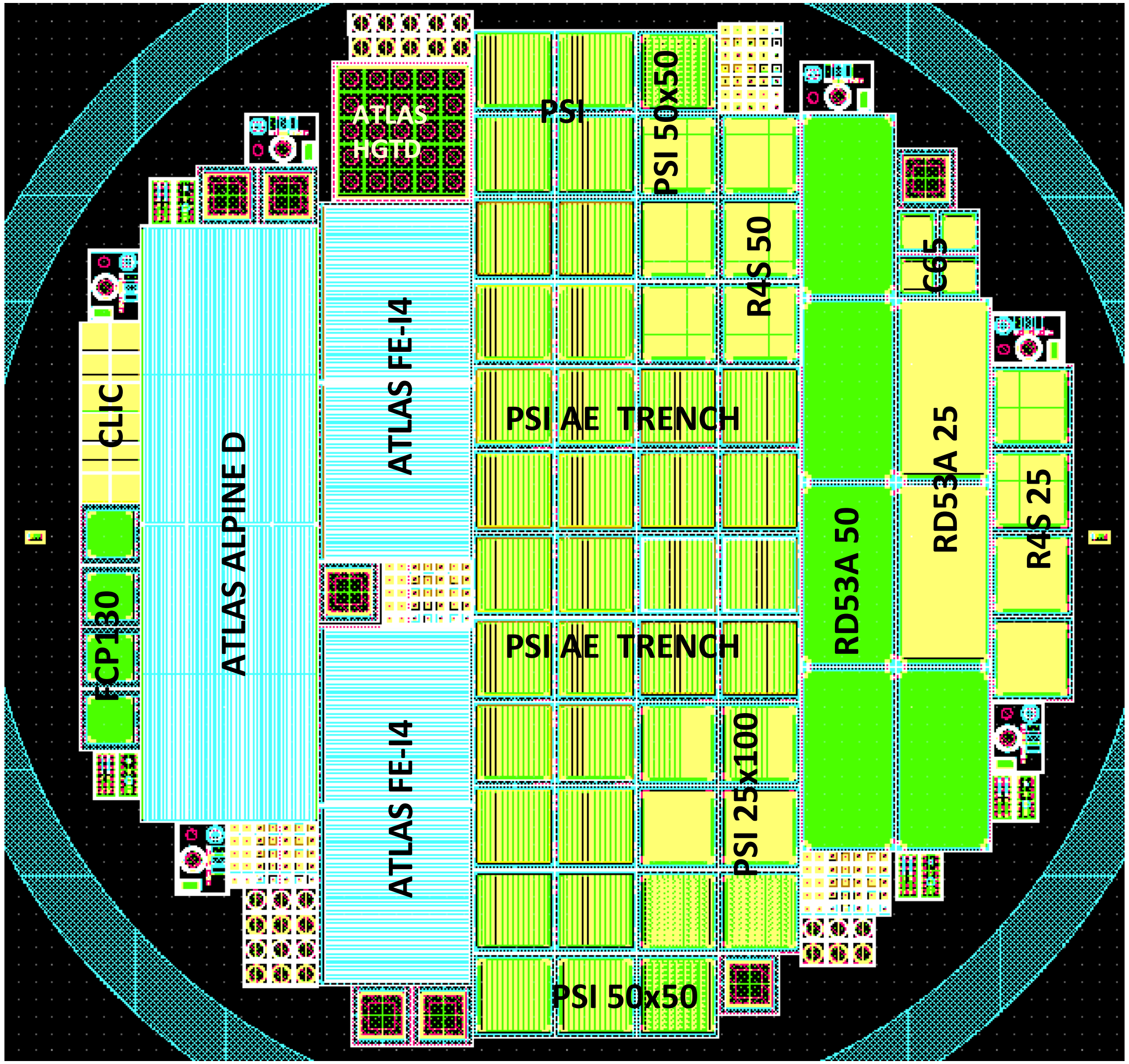


@ 850V bias the module died

INFN Planar Active/Slim Edge Submission at FBK

The Planar Pixel Active Edge Batch was completed by end 2016

FBK measured all the wafers (IV on all sensors and TS, CV on diodes) then removed temporary metal on first two wafers (Feb 2017)



Pitch in µm

PSI46dig (CMS)
- 100 x 150 std
- 50 x 50 adapt.
- 25 x 100 adapt.

FCP130 (New Fermilab roc)
- 30 x 100

RD53A
- 50 x 50
- 25 x 100

FE-I4 (ATLAS) single & double
- 50 x 250 std

R4S new PSI small pitch roc
- 50 x 50
- 25 x 100

CHIPIX 65nm prototype 64x64 pixels
- 50 x 50
- 25 x 100

CLIC-PIX
- 25 x 25

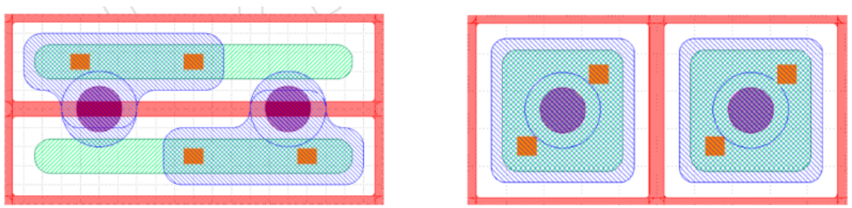
Staggered Trench implemented in standard PSI & ATLAS pixels

Wafers now at IZM Berlin

CMS: the HPK Planar Pixel Common Submission

The order consists of:

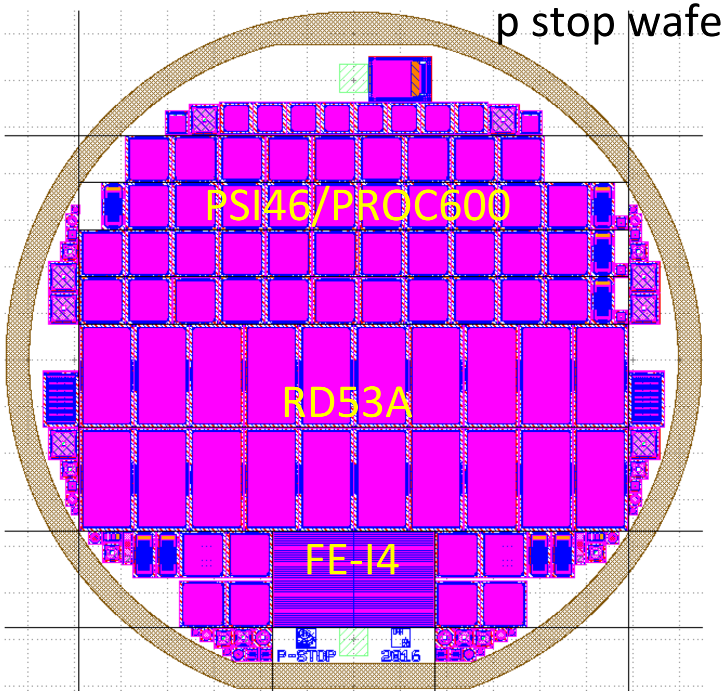
- 35 wafers 6” n^{+}-p FZ
  - 150 mm, no handle wafer
  - 150 mm + 50 mm Si-Si direct bond
  - Deep diffused 150 mm + 50mm
- Resistivity: 1-5 kΩcm, [O]=1.5E16 - 6.5E17
- Pixel Isolation: 25 wafers p-stop, 10 p-spray
- Sensors for PSI46dig/PROC600, FE-I4, ROC4sens, FCP130, RD53A (and CHIPIX65)



- Status: All p-stop and p-spray wafers received
- Received measurements from HPK
- Sensors now at CMS Institutes for characterization

Qty	Isolation	Material
10	p-stop	direct bond
10	p-stop	no handle
5	p-stop	deep diffused
10	p-spray	direct bond

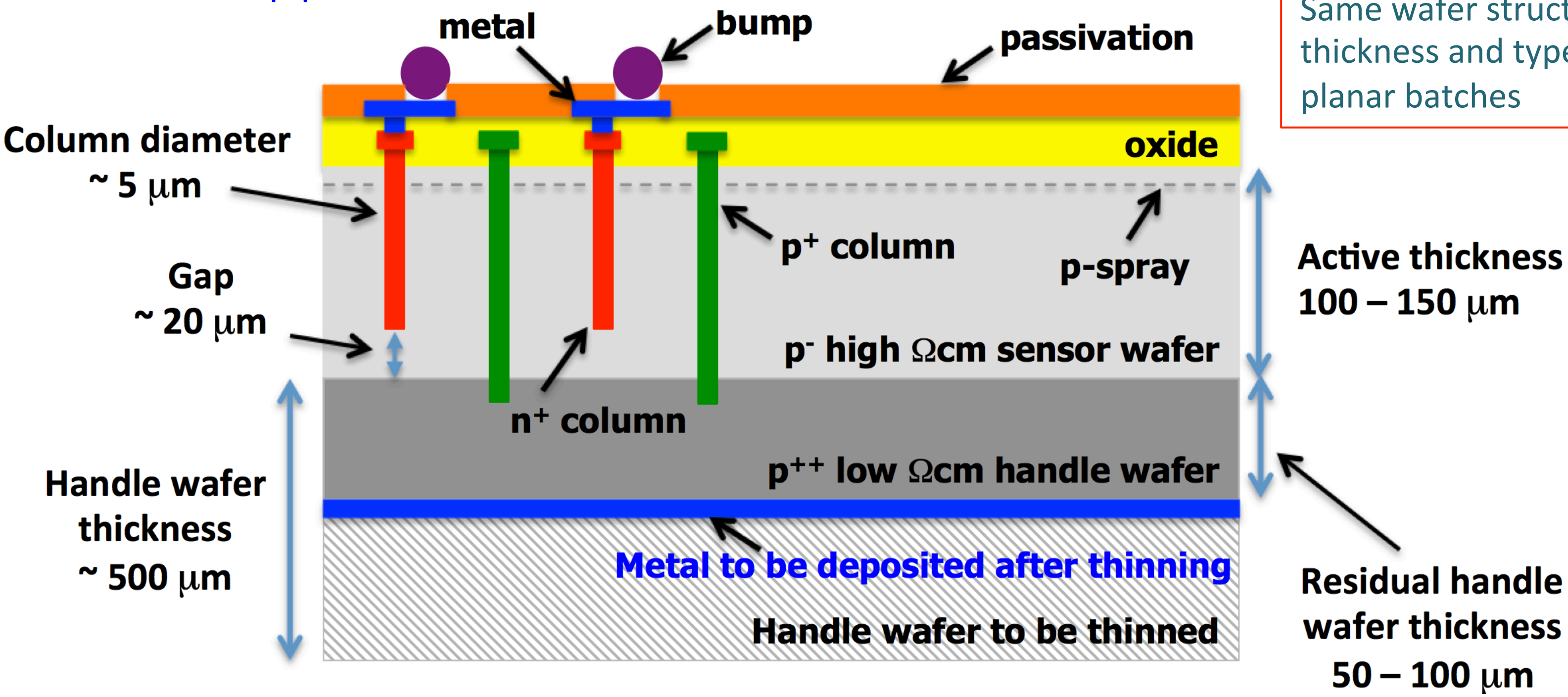
p stop wafer



J. Schwandt, G. Steinbrück, E. Garutti, Uni-Hamburg

INFN-FBK R&D: 3D Columnar Devices Generalities

- Devices are Single Sided, top-only process. We also plan to thin wafers. TB data shown at this conference are from not thinned sensors; handle wafer back-side is not metallized
- Pixel Cell design with variety of collecting electrodes
- Different bump pad locations tested



Same wafer structure, thickness and type as in planar batches

Standard pixel prototypes

100 μm x 150 μm pitch

Readout by PSI46dig ROC

ATLAS FE-I4 50 μm x 250 μm pitch (TB results not shown in my talk)

Small pitch pixel prototypes

50 μm x 50 μm, 25 μm x 100 μm pitch and 50 μm x 100 μm (the latter not yet tested on beam, lab bench only)

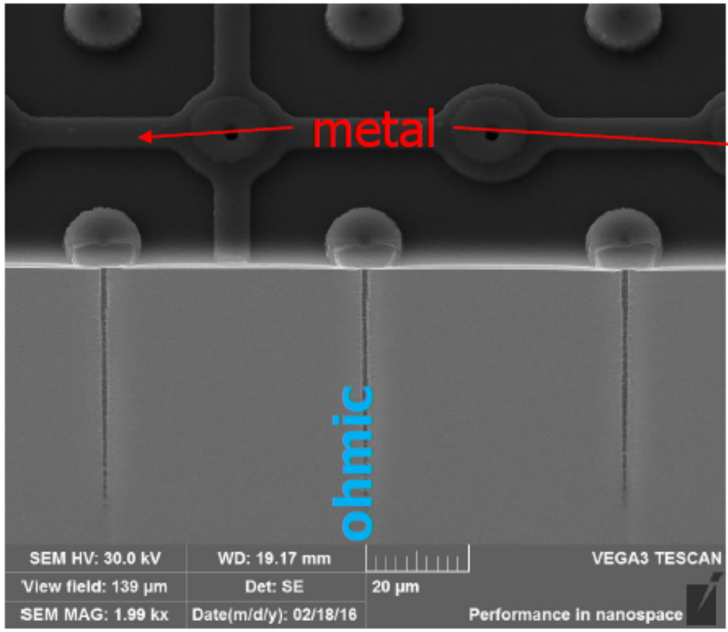
Multi-electrode single cell pixels

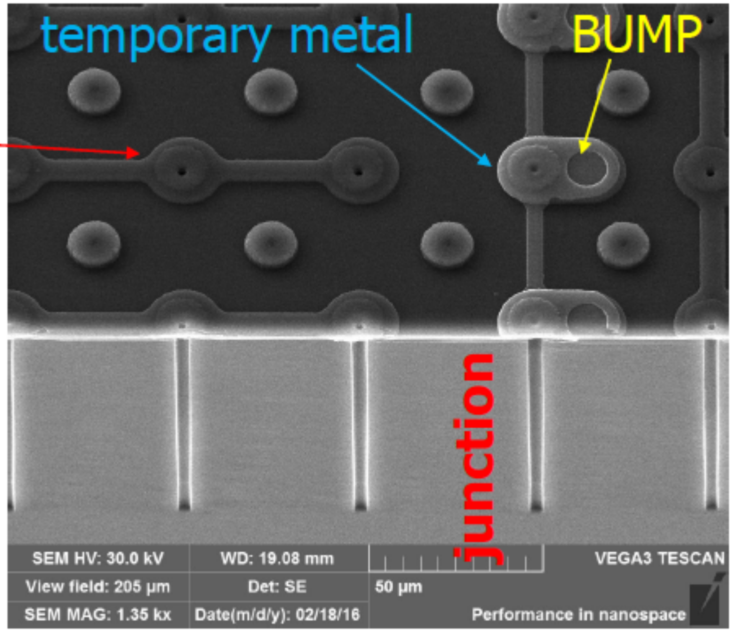
3D Pixel Production at FBK

FBK implemented a Top-side process: DRIE (Deep Reactive Ion Etching) technique
Very good control on column depths: junction columns must not reach the low resistivity handle wafer!

Scanning Electron Microscope pictures of columnar electrodes

G.F. Dalla Betta, ATLAS Trento Univ.

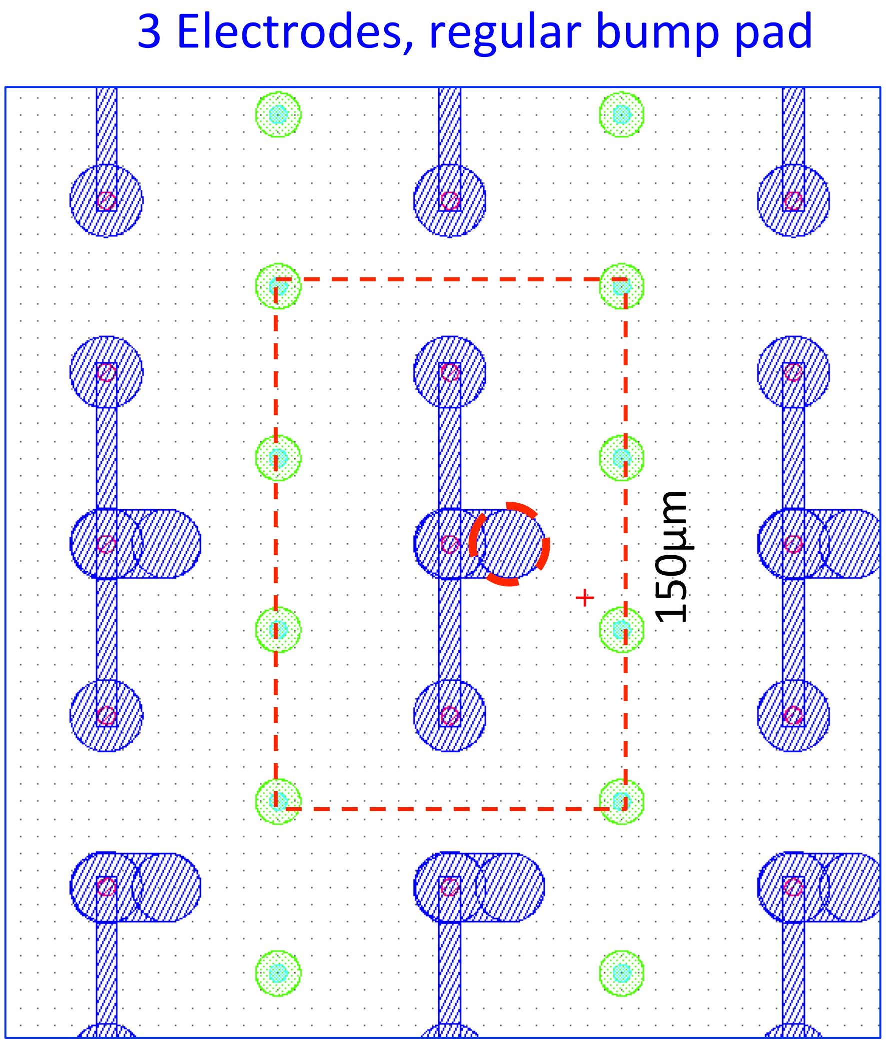


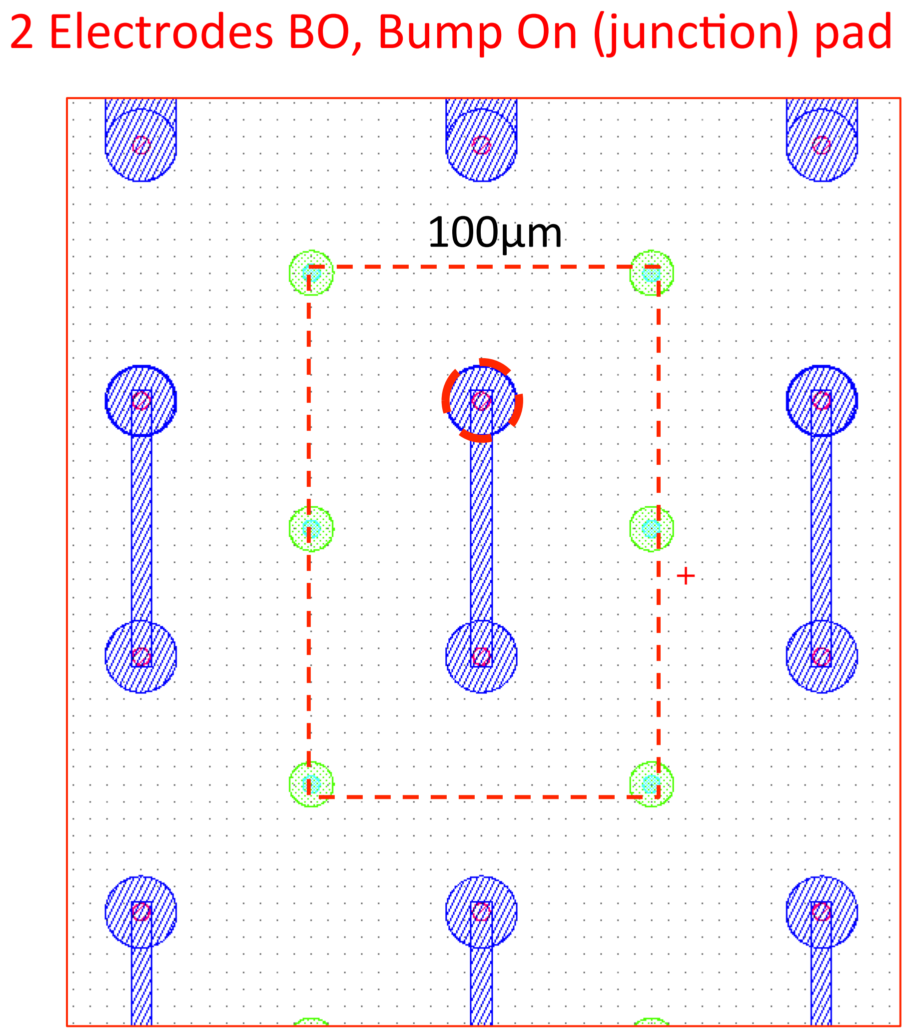


Small diameter columns: ~ 5µm give minimal inefficiencies even for tracks at 90deg incidence

3D sensors Indium bump bonded at Leonardo company (Italy) to PSI46dig ROC (Planars were bump bonded at IZM Berlin)
Overall rule: **all PSI46dig (100µm x 150µm) channels were bonded to pixels**, valid for all sensors, normal/small pitch ones

Design of 3D Pixel Cell 150µm x 100µm





Green: Omhic Columns

Red: Junction Columns

Red Dashed Lines to guide the eye on Pixel Cell and Bump Pad

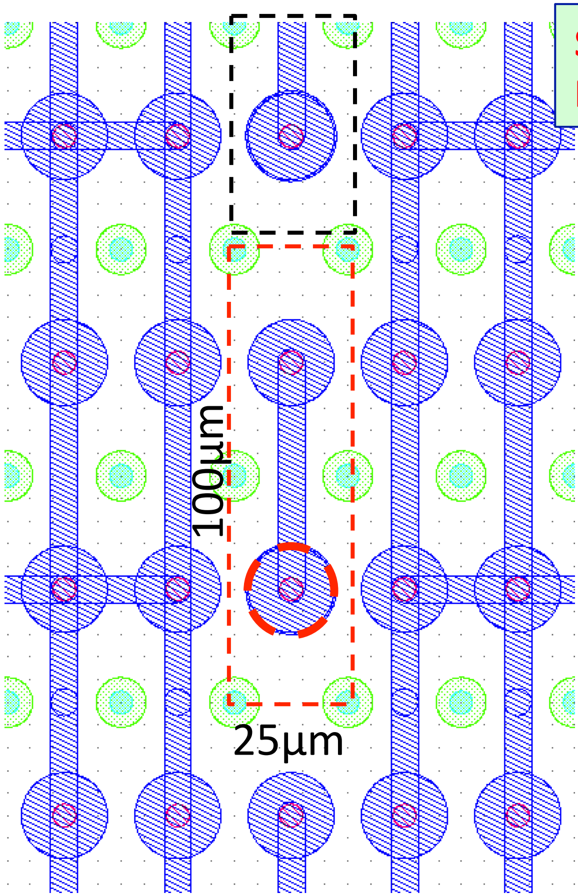
All Pixels Cells connected to PSI46 ROC

3D Pixel Cells 25µm x 100µm and 50µm x 50µm

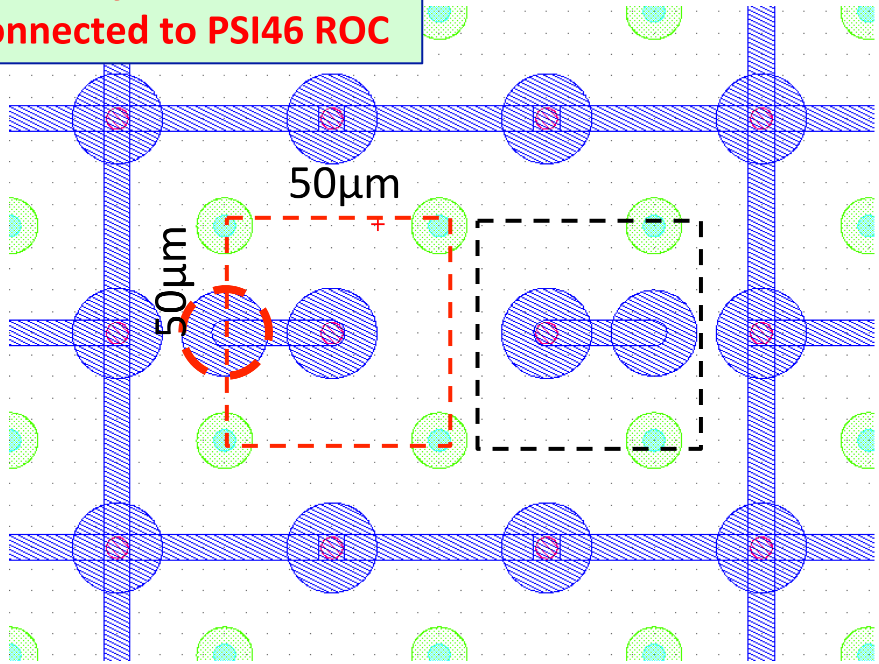
2 Electrodes BO, Bump On (junction) pad

1 Electrode, regular bump pad

Small Pitch pixels: only one out of six Pixels Cells is connected to PSI46 ROC



Entire 25µm column readout



Two adjacent 50µm pixels readout

Not readout Pixels Cells are shorted together

Green: Omhic Columns

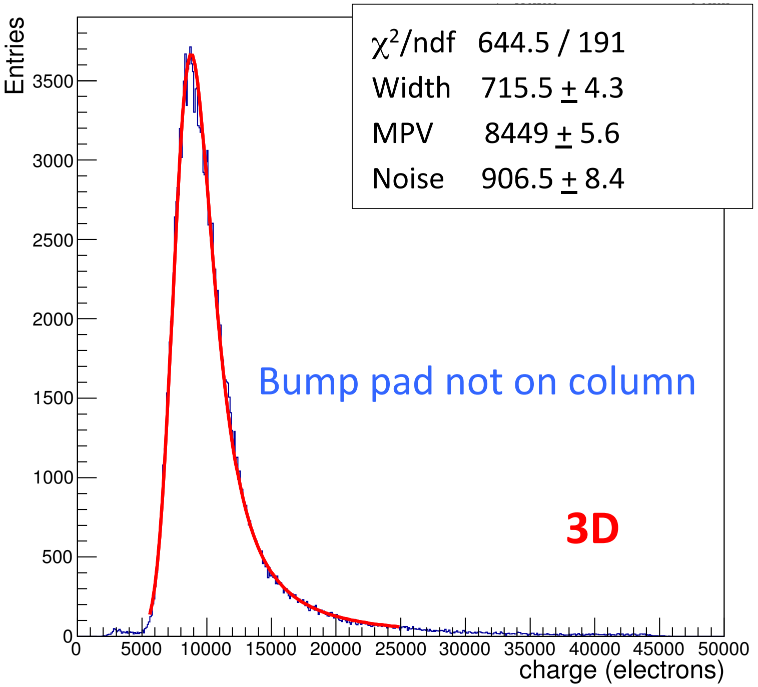
Red: Junction Columns

Dashed Lines are to guide the eye to identify Pixel Cell and Bump Pad

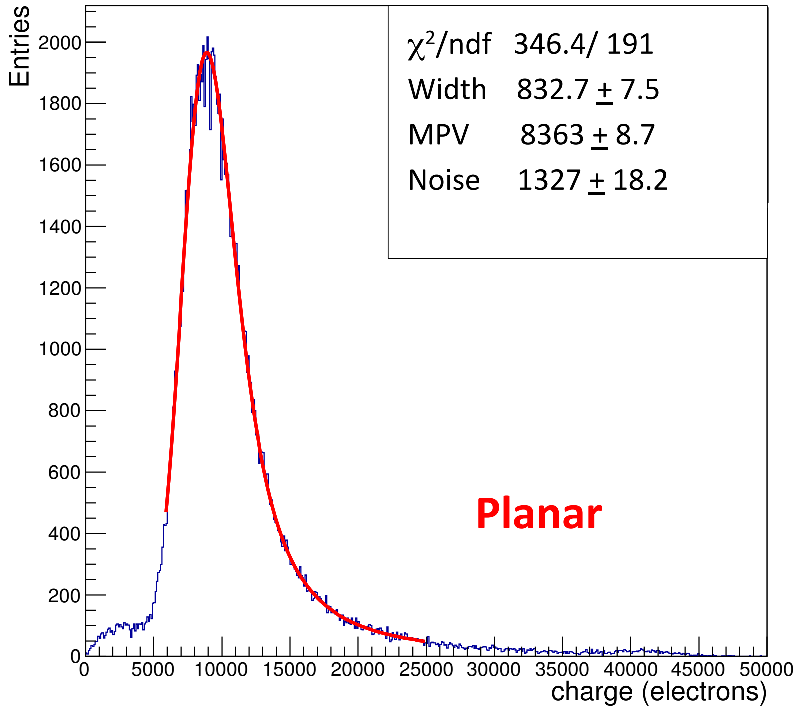
Beam test: Charge Collected in 130µm 3D Compared to Planar

Standard pixel prototypes **100x150 µm**

Planar and 3D prototypes on the same beam test session



W76_1-56B (3D) – 2E 100x150 µm @40V



W75-1_2-63D (Planar) – 100x150 µm@90V

Charge collection performance on 3D pixels is the same as planar ones, which have to be operated at higher V_{bias}

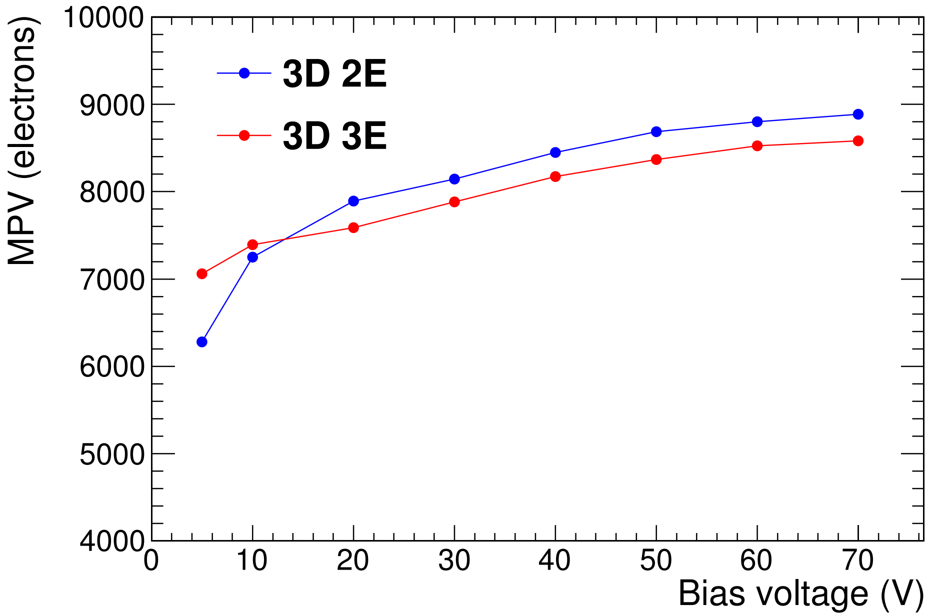
Beam test: Charge Collected in 130µm 3D Compared to Planar

Standard 100x150 µm pitch pixel, 130 µm thickness

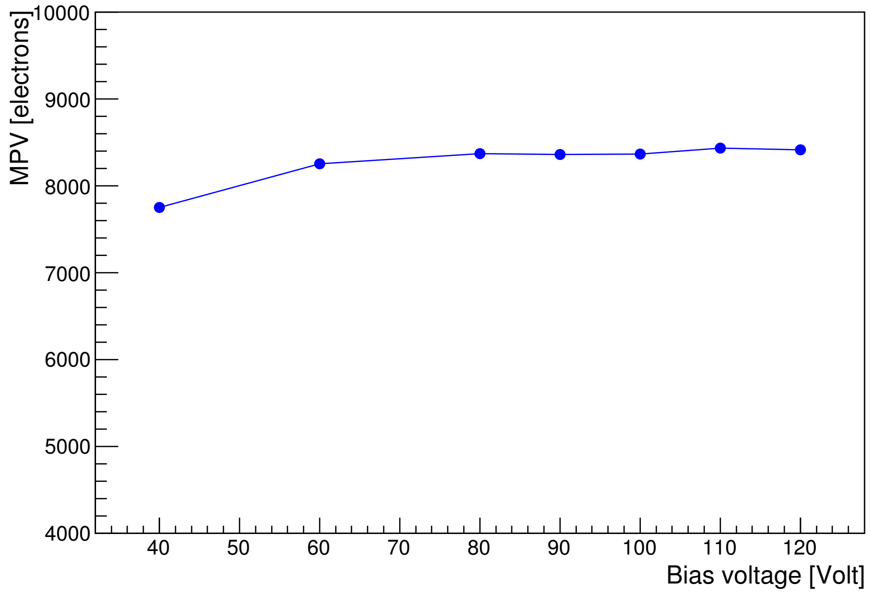
Tracks orthogonal to the detector

- Cluster size = 1 selection
- Tracking telescope predicted track impact on the selected cell in a fiducial window smaller than the pixel size

Charge collected vs V_{bias} 3D pixels



Charge collected vs V_{bias} planar pixels



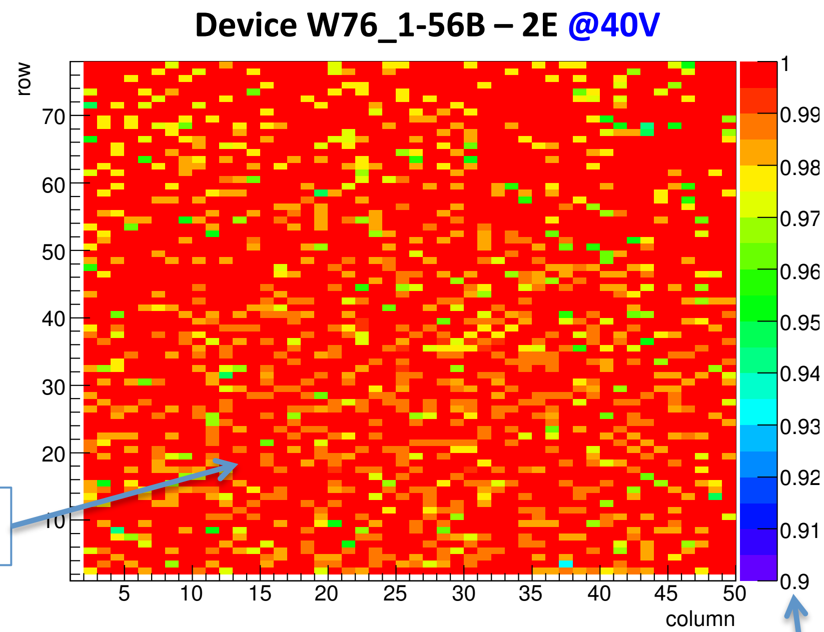
- Systematic uncertainties have been estimated to be of the order of 5%
- Absolute calibration not performed, same conversion factor (internal calibration to electrons) applied to all ROCs: small variations ROC by ROC to be expected

3D Pixel detector: detection efficiency

Standard 100x150 µm pitch pixel

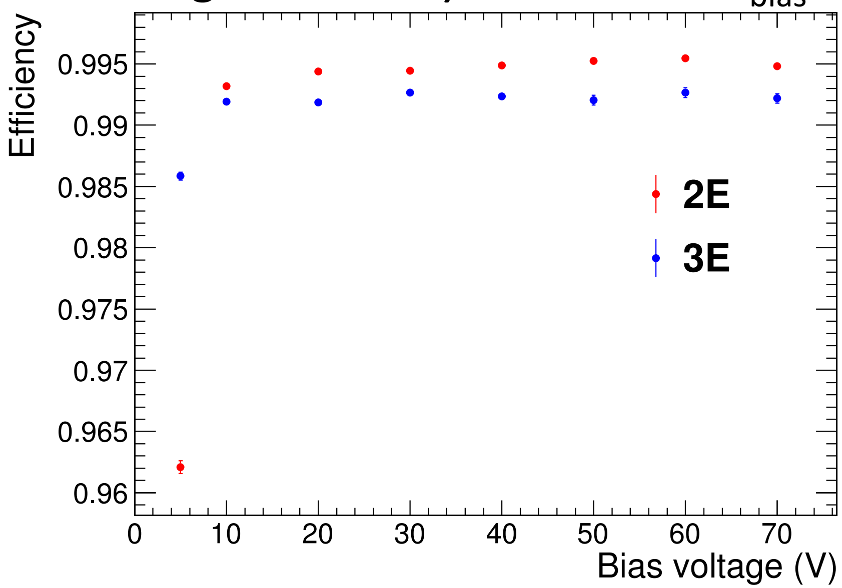
Orthogonal tracks

- Standard track quality selection
- The pixel pointed by the track or at least one of the 8 surrounding ones should be above threshold



Hit efficiency: 2D map

High efficiency also at low V_{bias}

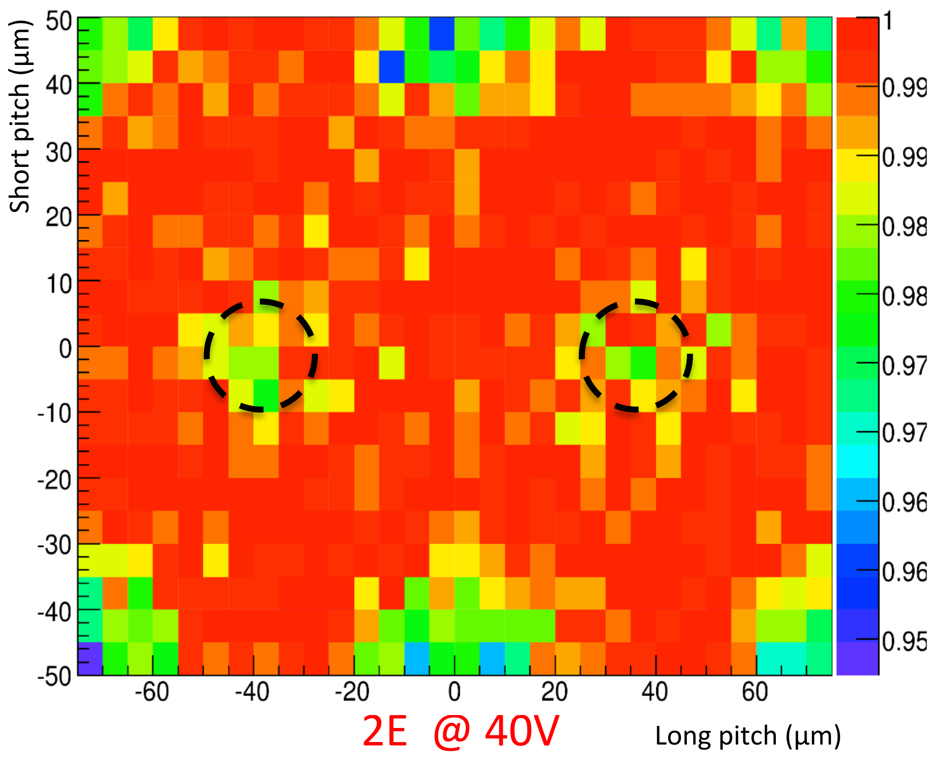


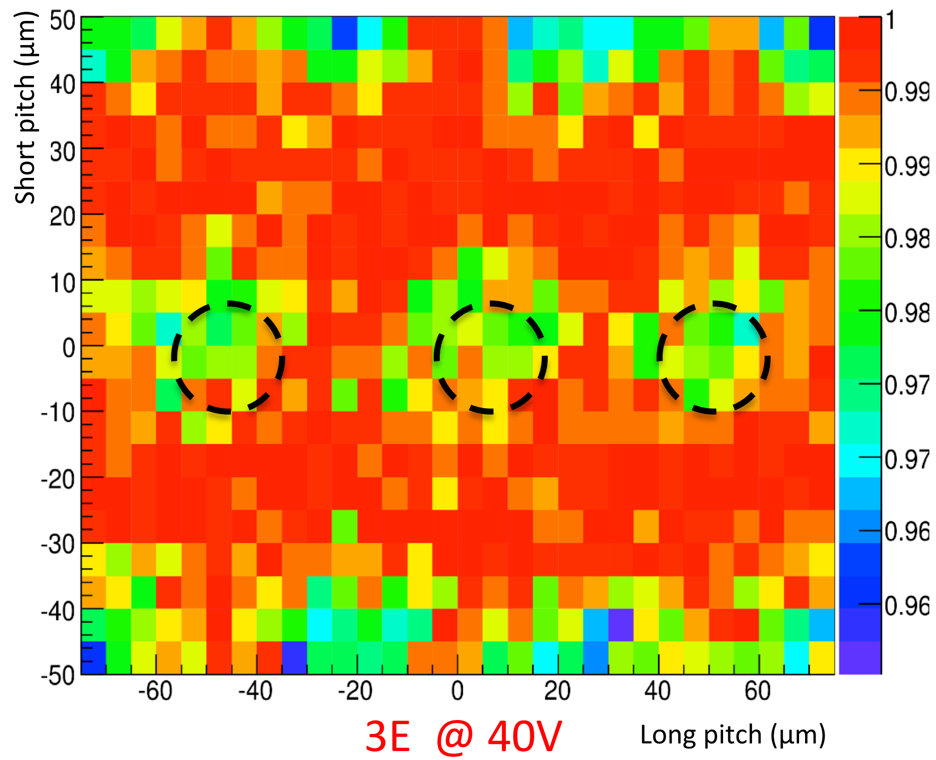
Efficiency is very high and uniform **0.9**

- 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%

3D Pixel Unit Cell: detection efficiency

- Standard 100x150 µm pitch pixel
- Different cell column design: 2 or 3 junction electrodes per cell, 6 or 8 Ohmic columns shared between adjacent cells
- Orthogonal tracks
  - All Pixel Unit Cells (4160) overlapped on a single cell: hit efficiency 2D map





Visible effect of columns volume

Smaller charge collection efficiency for tracks pointing to Junction columns

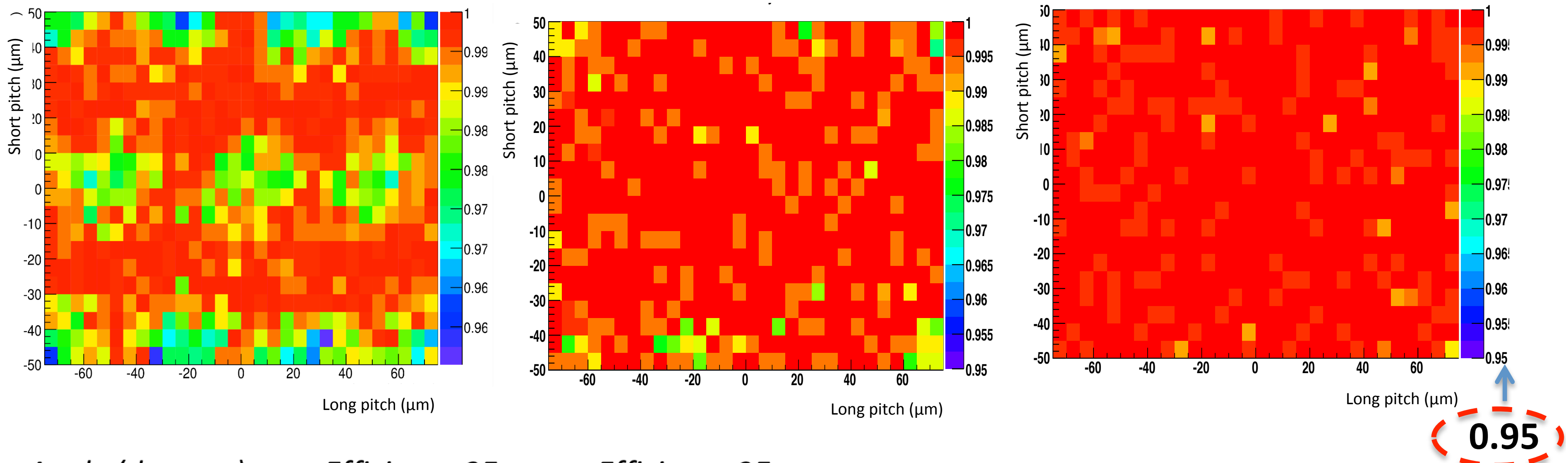
Lowest charge collection efficiency values located on tracks pointing to Ohmic columns

3D Pixel Unit Cell detection efficiency: tilted

All Pixel Unit Cells (4160) overlapped on a single cell

3D Module **W76_2-56D**-3E @ 40V

Orthogonal tracks | 5 degrees tilted sensor | 10 degrees tilted sensor



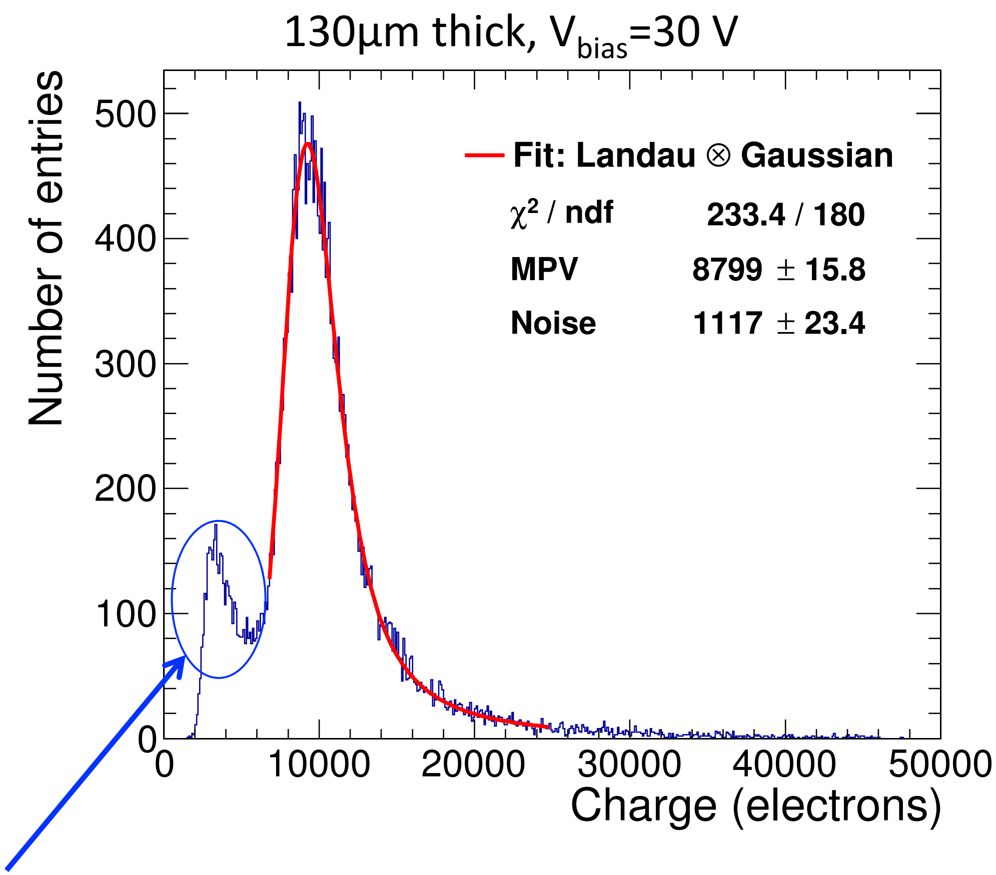
Angle (degrees)	*Efficiency 3E*	*Efficiency 2E*
0	**99.27%**	**99.45%**
5	**99.77%**	**99.85%**
10	**99.88%**	**99.87%**
max Δ Efficiency	**0.62%**	**0.43%**

Measured efficiency for inclined tracks

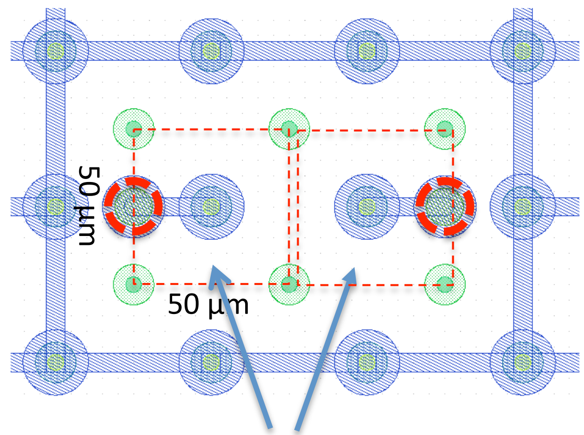
Almost full geometrical factor recovered

- 3E Detector Efficiency by +0.6%
  - Fraction of column area ~0.8%
- 2E Detector Efficiency by +0.4%
  - Fraction of column area ~0.5%

Collected Charge on Small Pitch 3D Pixel: 50 x 50 μm²



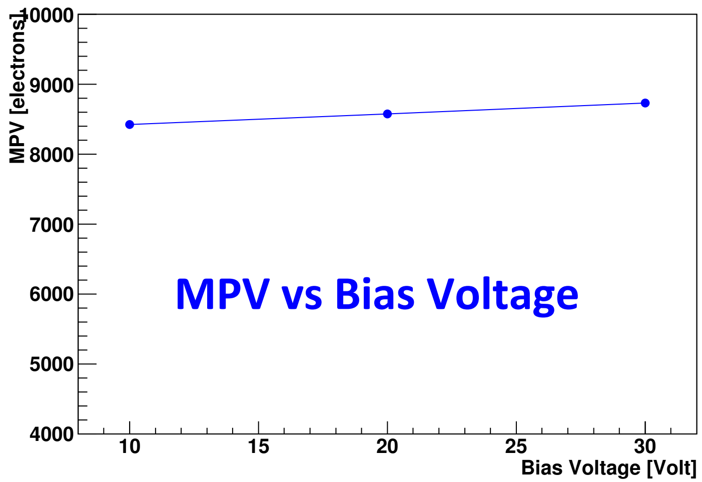
Charge distribution histogram filled with cluster size=1
Charge above threshold shared by not readout adjacent pixels. Effect over 3 out of 4 cell sides



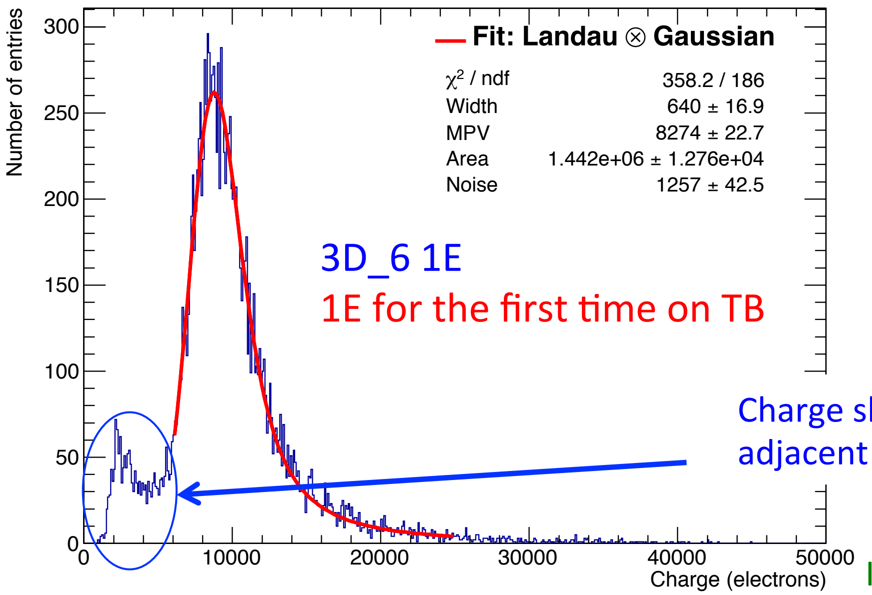
Two adjacent double columns pixel readout ROC (PSI46dig) fully connected

Red circles mark the bump positions

Sensitive area readout: 1/6



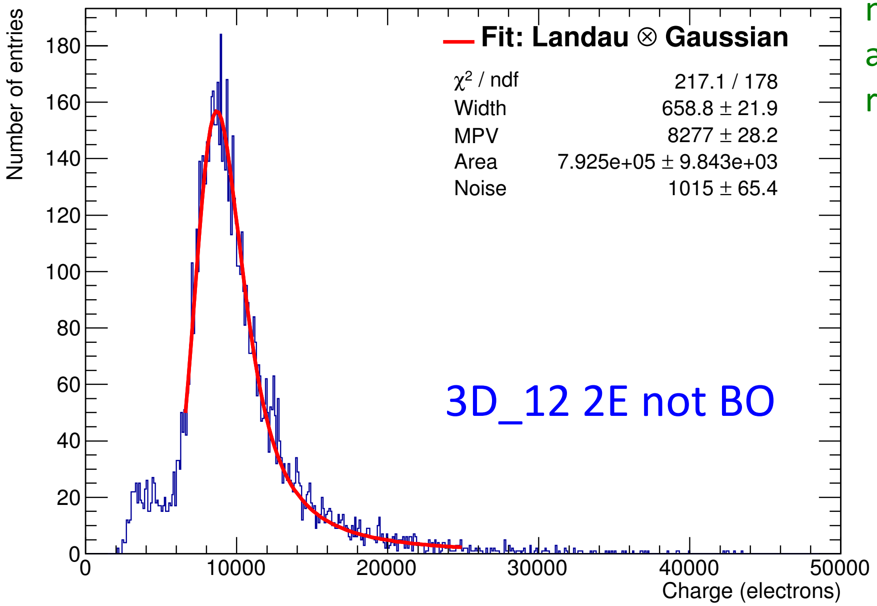
TB Feb 2017 Collected Charge on Small Pitch 3D Pixel: 25 x 100 µm^2

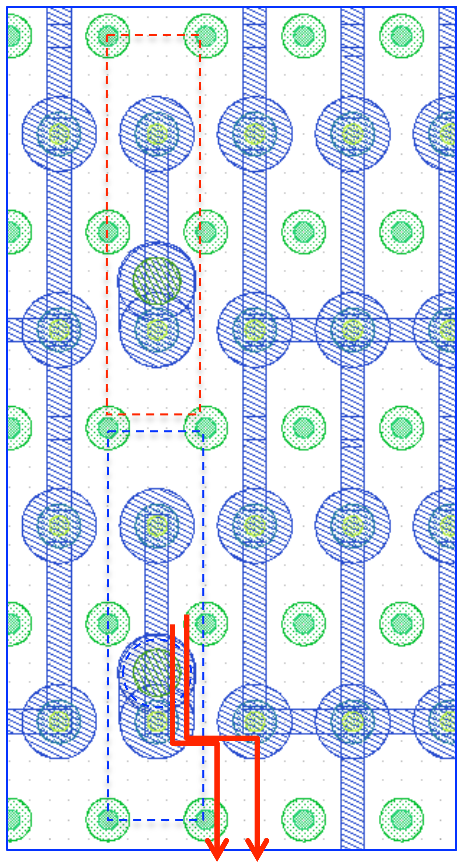


Due to the small readout area, getting statistically significant samples requires a lot of time to collect data on TB !

Charge shared with not readout adjacent pixels.

In prototype small pitch sensors, five out of six collected events do not point to readout pixels, then applying quality cuts strongly reduces data sample

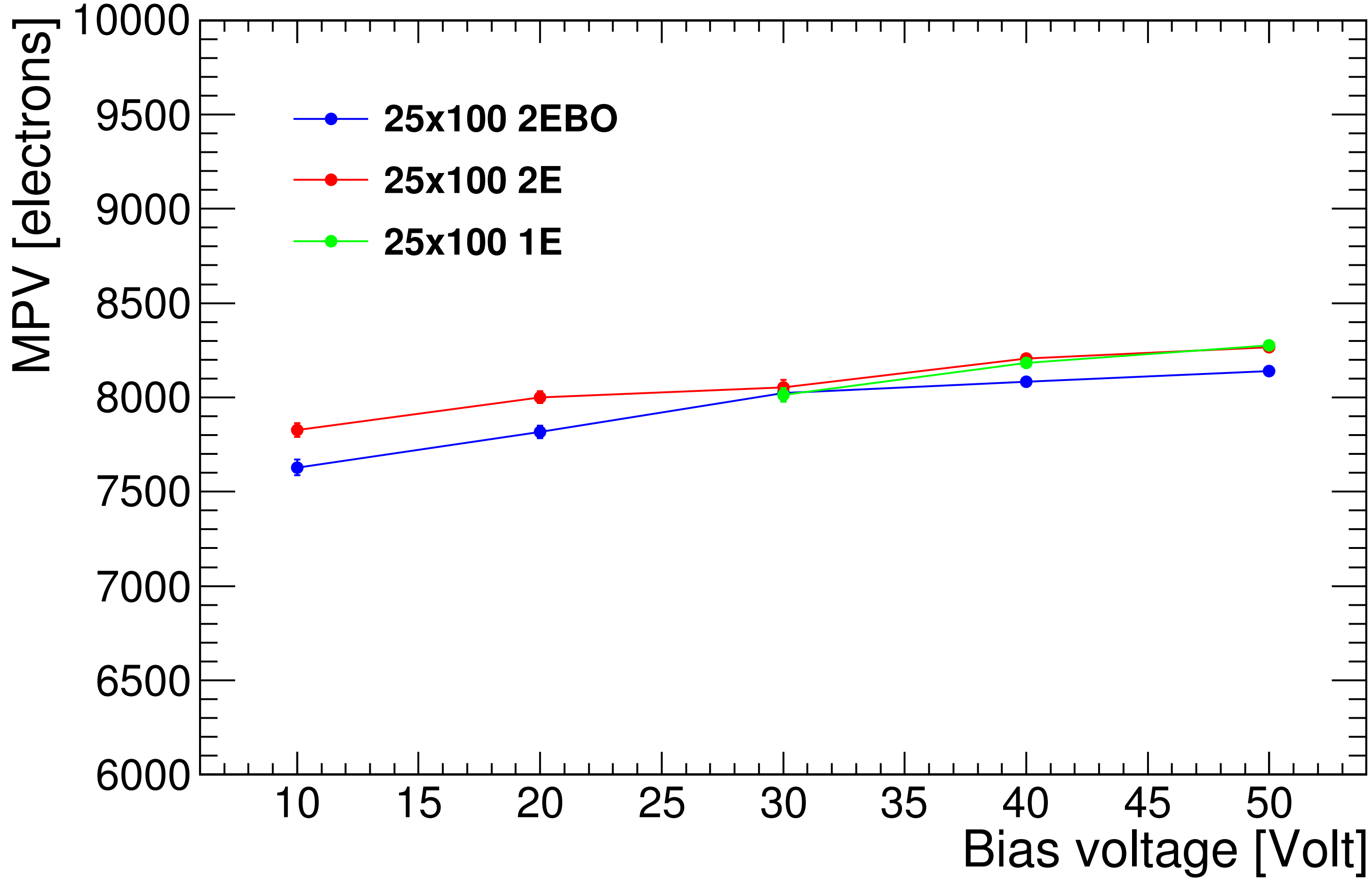




2µm distance!

Example of bump pad NOT on column: **25µm Pitch is extremely challenging design!** Note the distance between blue metal (Gnd) bump pads and green Ohmic columns (V_{bias})

Collected Charge vs Bias Voltage in 3D Pixel 25 x 100 μm^2



No striking differences among the three 25μm pitch 3D prototypes, they were all excellent in the beam test. Need to verify performance after irradiation

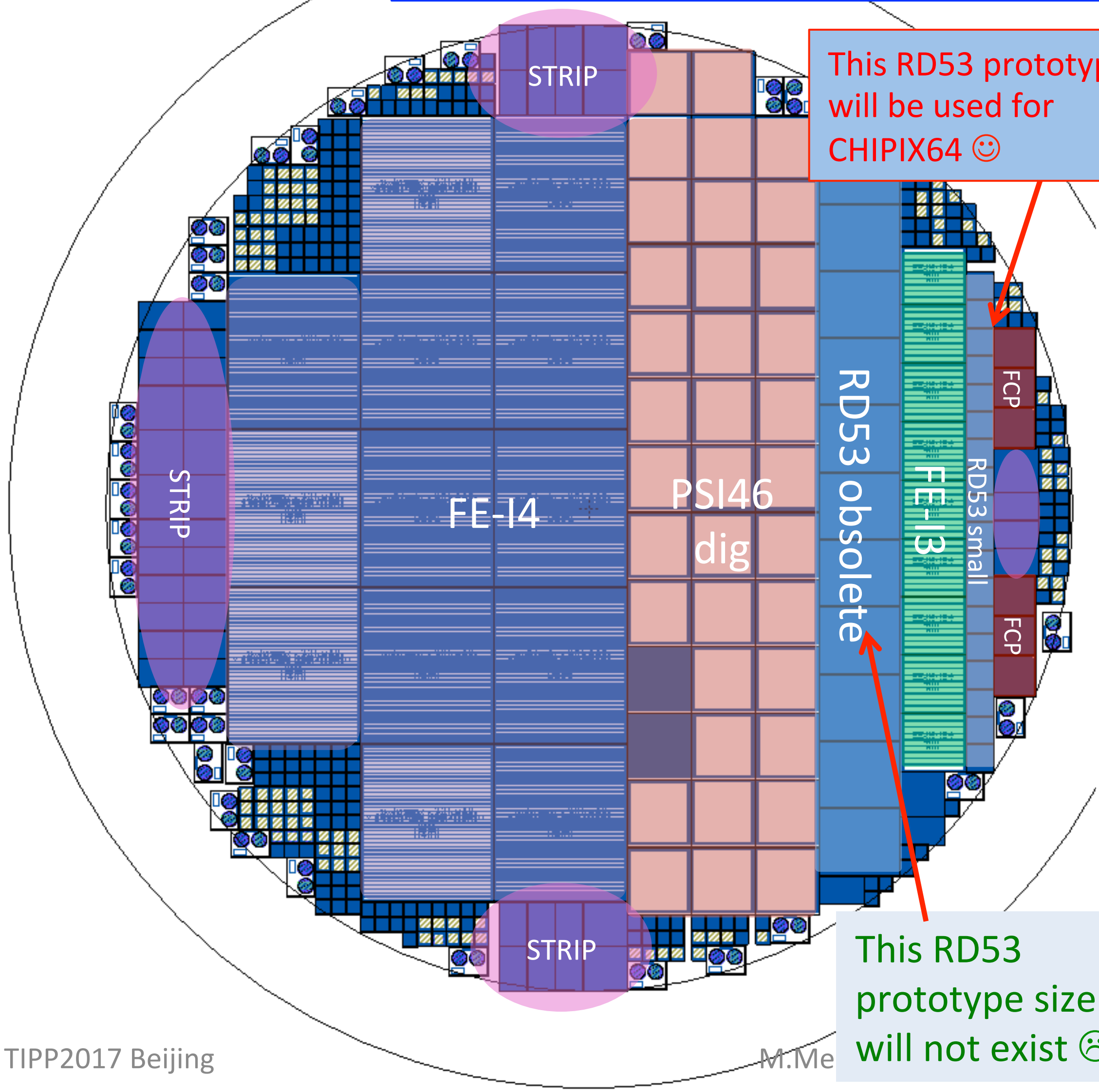
Plans and Conclusions

- New 3D batch with **AIDA-2020** at FBK in production: mainly aiming at RD53A and small pitch
- Planar Active Edge with **AIDA-2020** planned, small pitch sensors, with designs from CMS, ATLAS, CLICpix
- **New irradiations** to be performed in summer with 24GeV protons up to $5x10^{15}$ neq/cm^2 at CERN-IRRAD and fast neutrons up to $7\text{-}10x10^{15}$ neq/cm^2 at JSI Ljubliana for both **planar and 3D hybrid modules** with PSI46dig (we are still limited in fluence by present ROCs radiation hardness)
- **Bump Bonding yield** (both IZM and Leonardo) is extremely **high**, less than one missing bump per module (4160 Bump Bonds/module)
- **Thin planar pixel sensors from first FBK batch**: very good behaviour before irradiation and high efficiency after proton irradiation to $3x10^{15}$ neq/cm^2
- **New thin 3D columnar pixel sensors** tested on beam before irradiation are excellent both in charge collection and efficiency. They can be operated at moderate bias voltage, and we will verify performance on beam test after irradiation. **3D Pixels are very promising candidates for inner layers tracker upgrades of the High Luminosity LHC**

Back Up

3D Pixel First Batch Wafer Layout

Many different pixel geometries and pitch options. Sensors geometry is quite complex: a lot of work to measure sensor efficiencies, charge and resolution (if at all possible)



This RD53 prototype will be used for CHIPIX64 ☺

This RD53 prototype size will not exist ☹

- FE-I4 (ATLAS)
  - 50 x 250 (2E) std
  - 50 x 50 (1E)
  - 25 x 100 (1E and 2E)
  - 25 x 500 (1E)
- FE-I3 (ATLAS)
  - 50 x 50 (1E)
  - 25 x 100 (1E and 2E)
- PSI46dig (CMS)
  - 100 x 150 (2E and 3E) std
  - 50 x 50 (1E and 2E)
  - 50 x 100, 100 x 100 (2E + 4E)
  - 50 x 100, 100 X 150 (2E + 6E)
  - 25 x 100 (1E and 2E)
- FCP (Fermilab chip)
  - 30 x 100 (1E)
- RD53 (sensor size changed, now obsolete)
  - 50 x 50 (1E)
  - 25 x 100 (1E)
  - 25 x 100 (2E)

+ Test structures (strip, diodes, etc)

BCB on PSI46dig ROC Wafer

- **Wafermap and layer definition**

Gds-Layers# IZM:

20 – BCB (drawn structures will be BCB-free)
21 – UBM

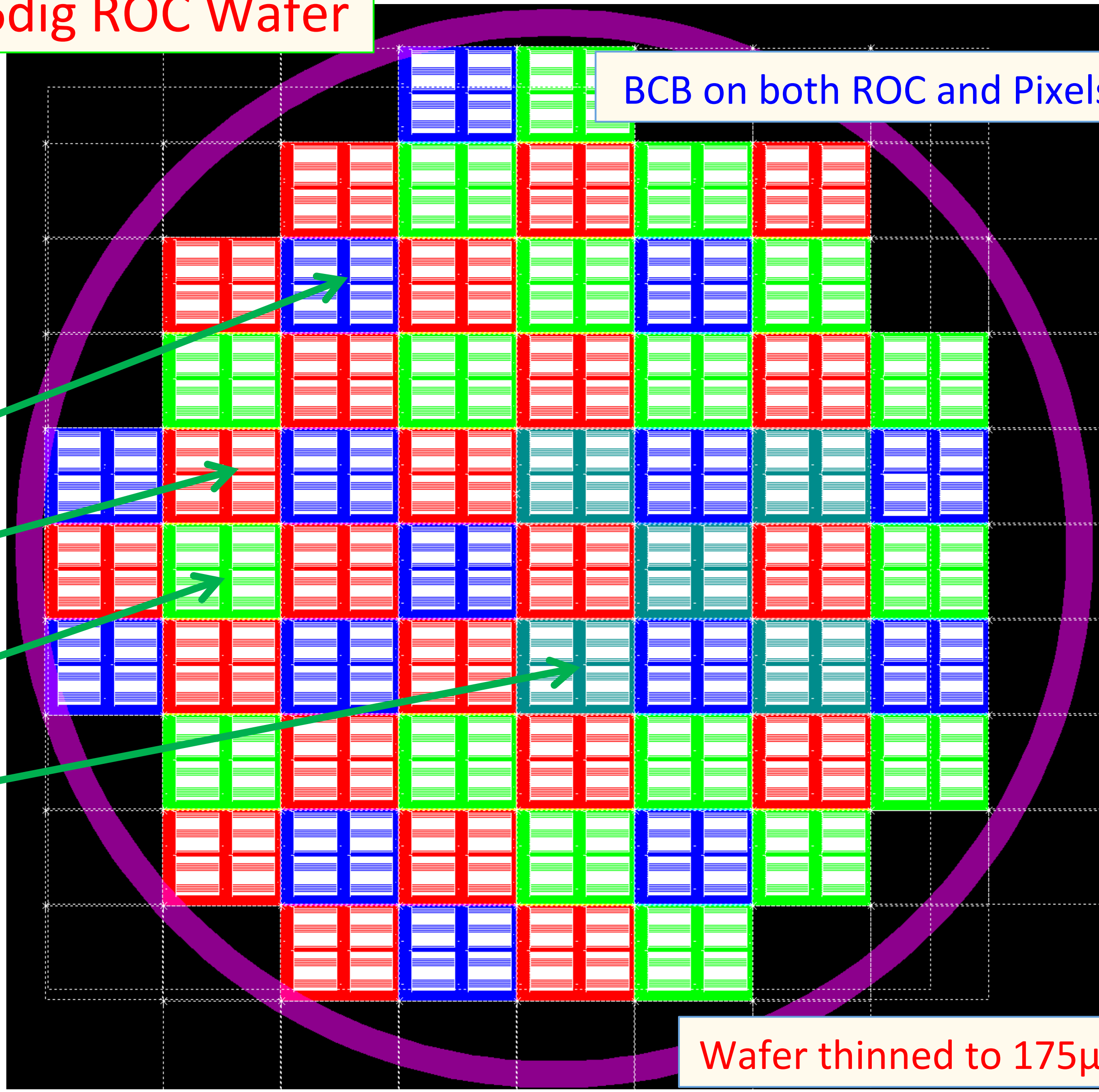
Reticle variants:

15x BCB-free (with GR-bumps)

23x frame mask (without GR-bumps)

18x full mask (without GR-Bumps)

5x full mask (with GR-bumps)



BCB on both ROC and Pixels!

Wafer thinned to 175µm

Could BCB around bumps help in reducing the mechanical stress on ROCs during wire-bonding and handling?

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