Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CMS Pixel detector development for the HL-LHC

J. Schwandt

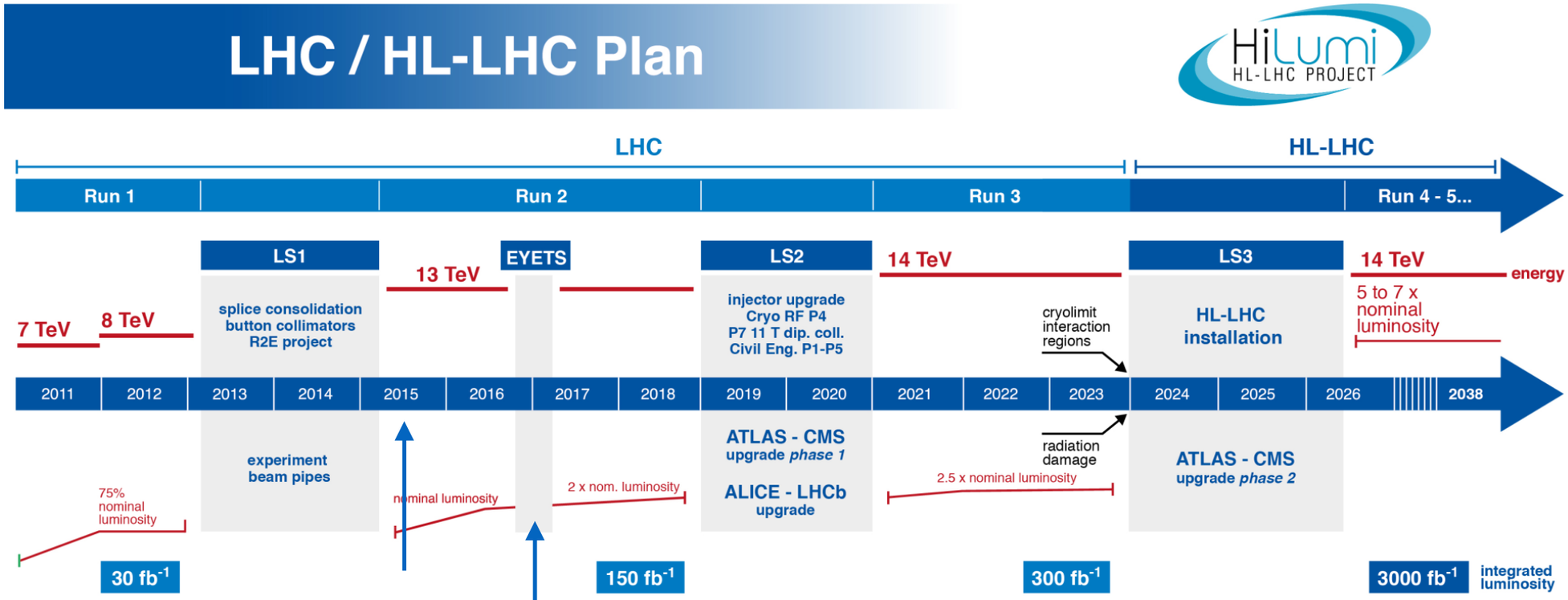
on behalf of the CMS Tracker Collaboration

Institute for Experimental Physics
University of Hamburg

HSTD11
OIST, Okinawa,Japan
10.12 - 15.12.2017

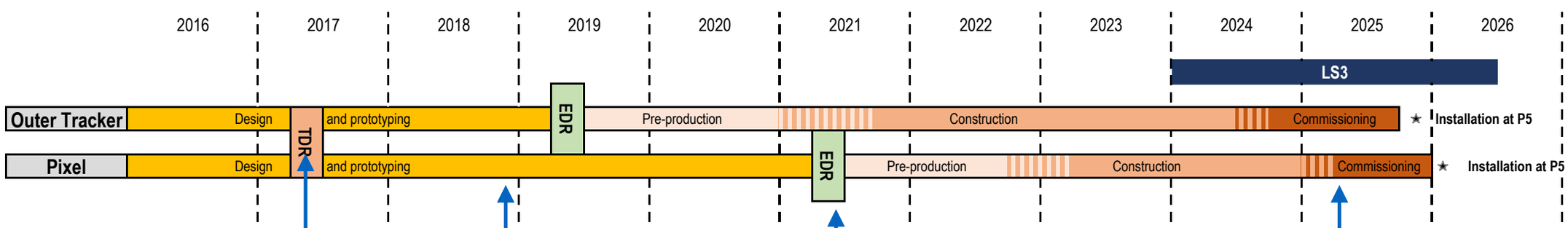
SPONSORED BY THE
Federal Ministry of Education and Research

HL-LHC & CMS TRACKER ROADMAP



CMS Technical Proposal & Scope Document (Q2/Q3 2015)

Installation of phase-I Pixels



Tracker TDR (Q4 2017)

Time for development

EDR date

Construction

THE PHASE II PIXEL UPGRADE

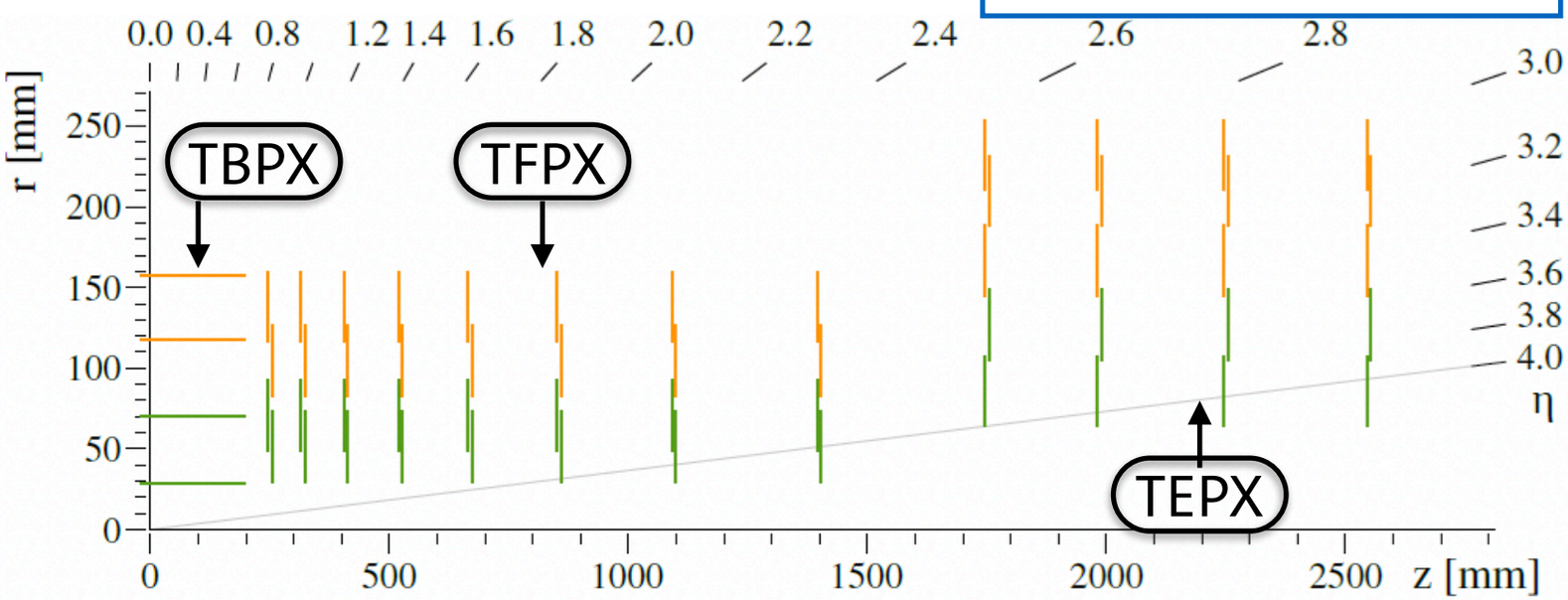
High-Luminosity LHC :

- Luminosity of 5-7.5x10^{34} $cm^{-2}s^{-1}$, up to 200 events/ 25 ns bunch crossing
- Maintain occupancy at the permille level and increase the spatial resolution

➡ Pixel size ~ 25x100 μm^2 or 50x50 μm^2 (currently 100x150 μm^2)

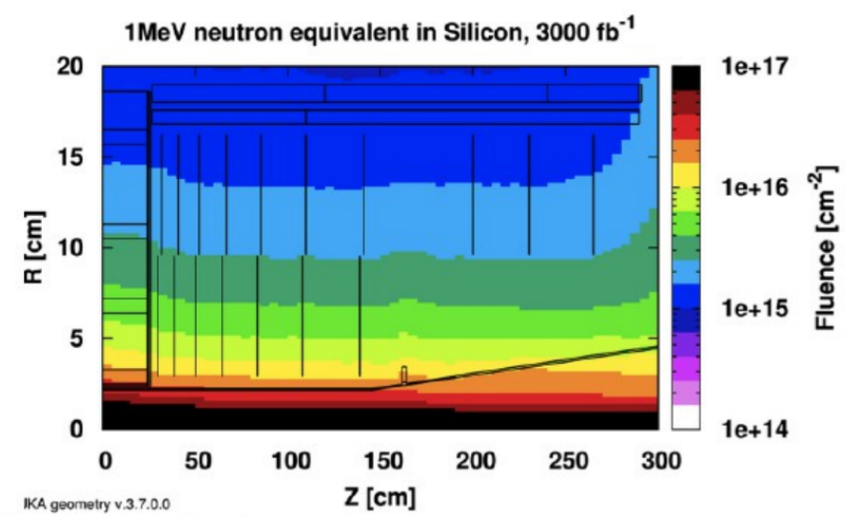
Pixel layout:

2x2 and 1x2 modules



Pixel detector (25 cm > R > 3 cm):

- 4 barrel layers à la phase I
- 12+12 discs (|η| up to 4)



Radiation tolerance for the 1st pixel layer after 3000 fb^{-1}:

- $\Phi_{eq} \approx 2.3 \times 10^{16}$ cm^{-2}, dose ≈ 12 MGy

3D or planar pixel sensors for the 1st layer?

- R&D in parallel. Both options described and costed in TDR.

THE PHASE II PIXEL UPGRADE

Simple mechanics:

- No turbines/blades in TFPX/TEPX

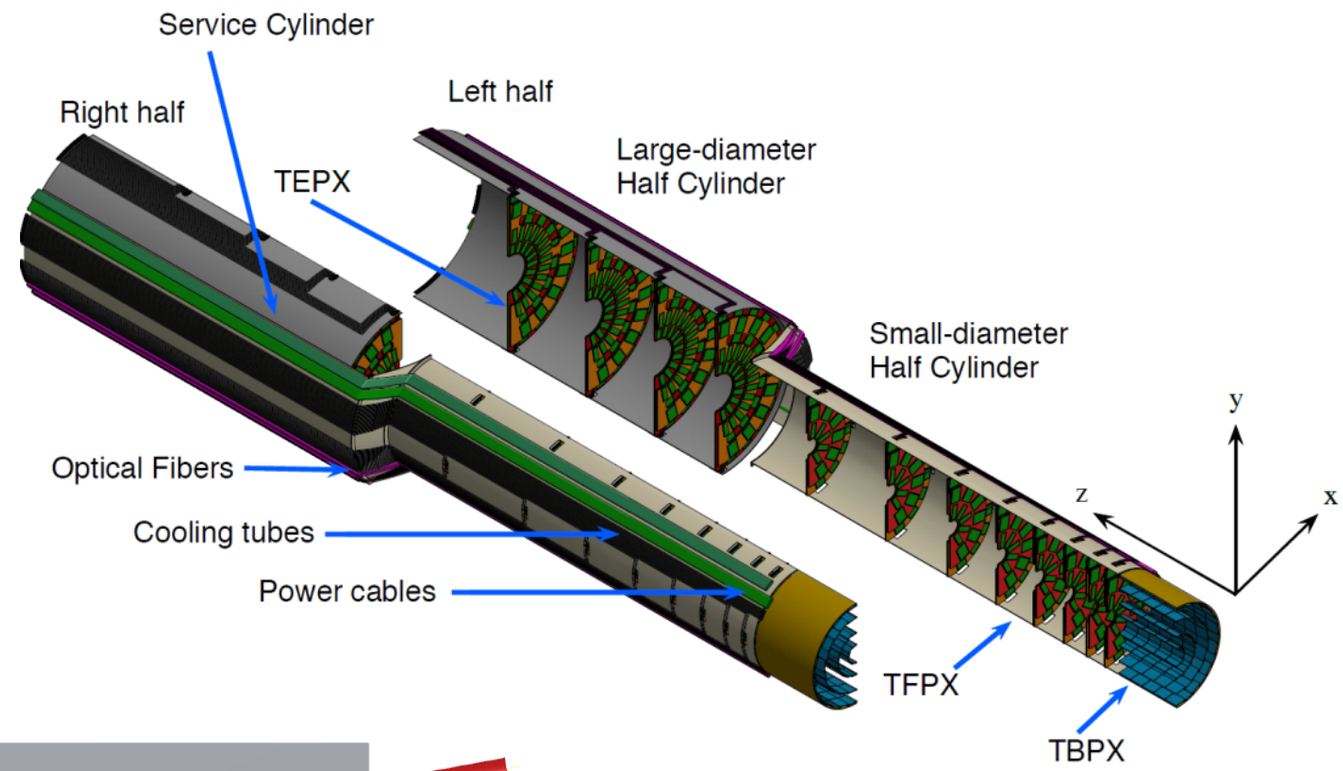
Only 2 module types:

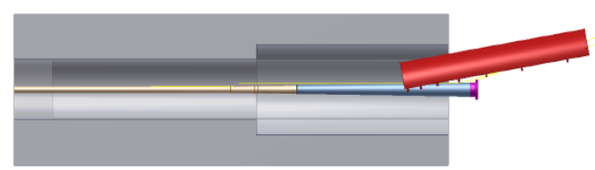
- 1x2 and 2x2

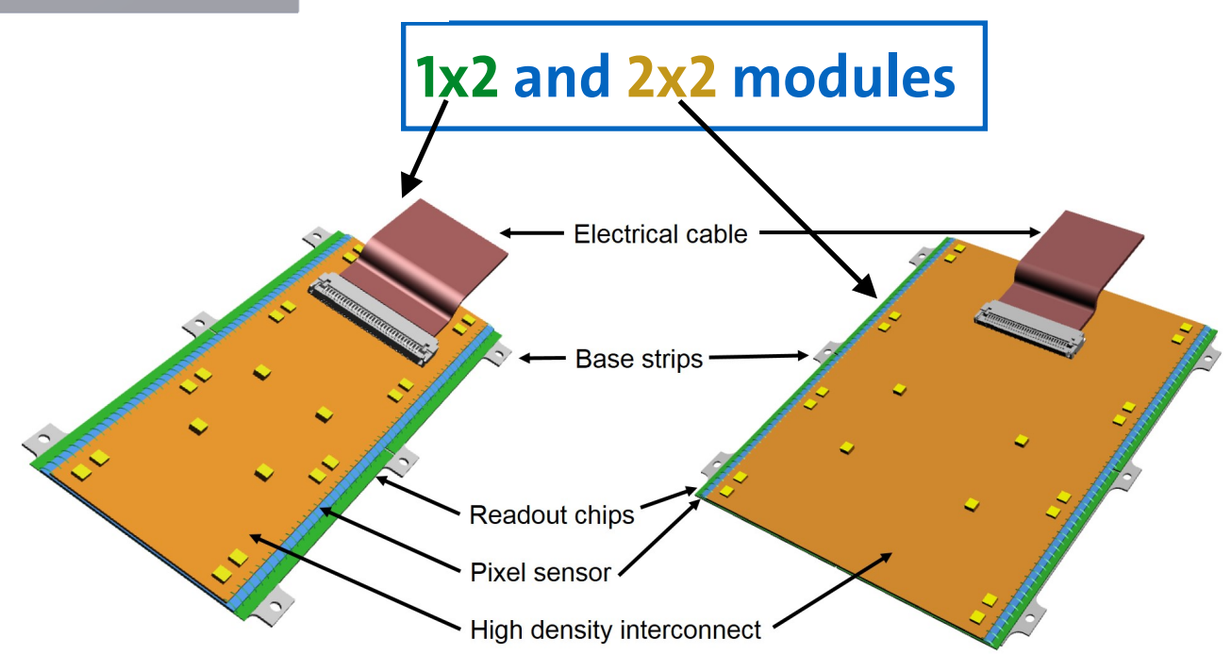
Step in the pixel envelope:

- To allow installation of central section with beam pipe in place

In total ~ 4.9 m² of Si, > 4300 modules







R&D PROGRAMS WITHIN CMS

Thin, small pitch planar pixel sensors:

- **HPK submission (n^+-p): Lead by UHH**
- INFN - FBK R&D program, together with ATLAS (see talk from M. Meschini at HSTD10 (2015))
  - 6” n^+-p, > 3 kΩ·cm, direct wafer bond
  - 100 µm and 130 µm active thickness
  - p-spray isolation
  - temporary metal for sensor testing
  - active edge / slim edge designs

First thin small pixel test sensors
work well, but radiation hardness has to be demonstrated

INFN/FBK

3D silicon pixel sensors:

- **CNM Barcelona**
- INFN - FBK R&D program, together with ATLAS (see talk from M. Meschini at HSTD10 (2015))

Successful production 3D sensors, first results on small pixels, rad. hardness studies to $2x10^{16}$ cm^2 to be done

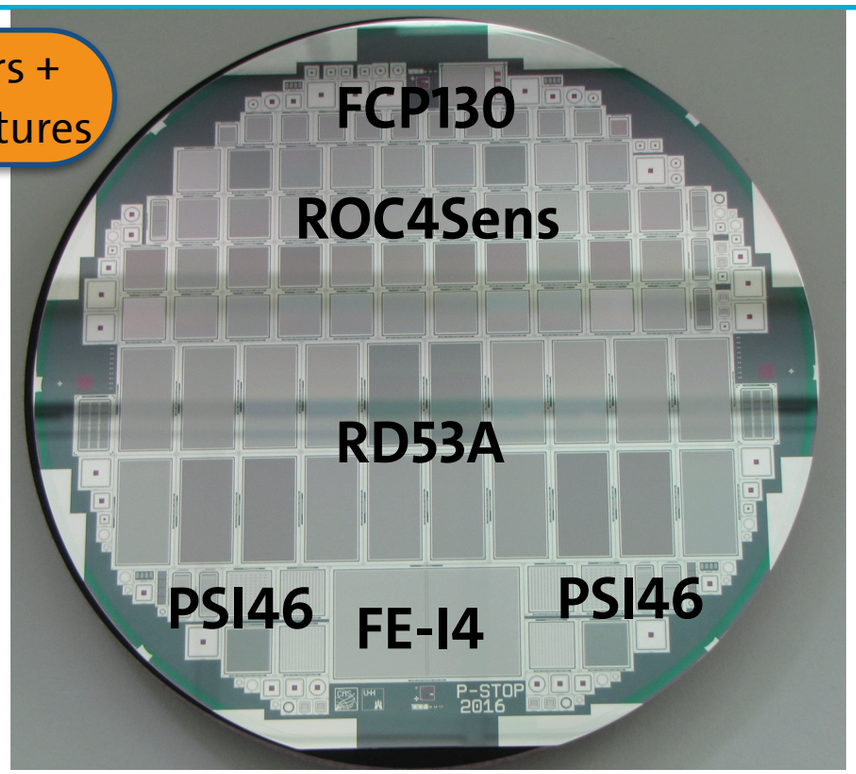
INFN/FBK
CNM

No fine pitch, radiation hard readout chip available in time for the TDR

- ROC4Sens (PSI R&D chip available since summer 2017)
- RD53A (prototype chip for phase 2, end of 2017)

HPK SUBMISSION: OVERVIEW

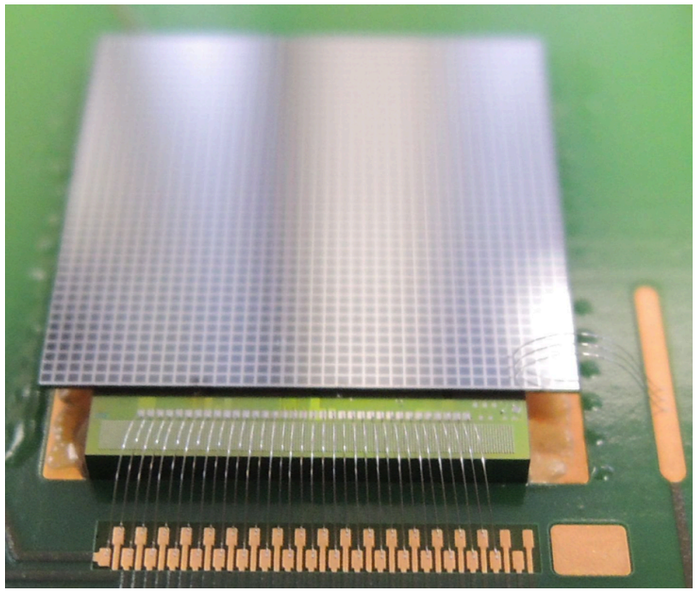
≈ 2945 sensors + 3400 test structures



Sensor order:

- 35 wafer 6” n^+-p FZ
  - 10 wafer with **150 µm thickness** (FTH150)
  - 20 wafer with **150 µm + 50 µm handle wafer** (FDB150)
  - 5 wafer with **150 µm deep diffused** (FDD150)
- Resistivity: 1 kΩ·cm - 5 kΩ·cm
- Isolation: 25 with **p-stop** (P) and 10 with **p-spray** (Y)
- Biasing schema: **none**, common **punch-through**, **polysilicon resistor**
- Backside grid for laser test

ROC4Sens module



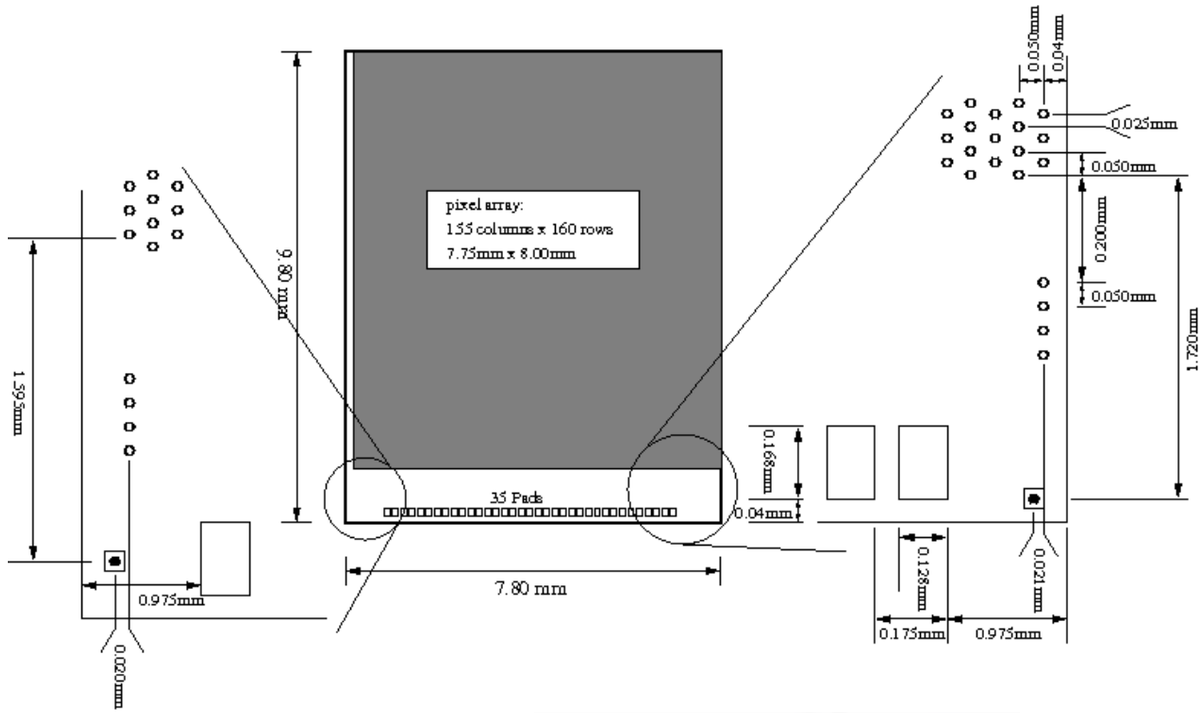
Bump-bonding at IZM:

- 8 wafers (2xFDB150P, 2xFTH150P, 2xFDD150P, 2xFTH150Y) have been processed
- 140 **ROC4Sens** modules (64 module + some test structures received)

THE ROC4SENS

ROC for small pitch sensor development from PSI:

- 50 x 50 µm² staggered bump bond pattern
- 155 columns x 160 row → 24800 pixels
- Size: 9.80x7.80 mm²
- Based on PSI46 (IBM 250 nm)
- Simple operation:
  - no DACs or other programming
  - no discriminator, threshold adjustment and trimming
  - small number of signals required
- Analog pulse height is read out
- Suitable for test beams and source measurements with asynchronous hits (no synchronous sampling with external clock)
- Radiation hardness > 5 MGy (expected)
- Readout based on CMS PIXEL-DTB



HPK SENSORS FOR THE ROC4SENS

p-stop designs:

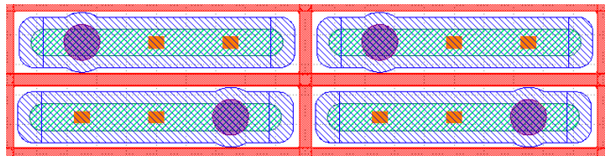
- 8 variants for 100x25 µm²
  - no bias (default), 2 x common punch through, 2 x poly Si
  - + 1 sensor for routing testing
  - + 1 sensor bricked
  - + 1 sensor to test limits
- 9 variants for 50x50 µm²
  - no bias (default)
  - open p-stop
  - 3 x common punch through
  - 2 x poly Si
  - + 1 sensor bricked
  - + 1 sensor to test limits

p-spray designs:

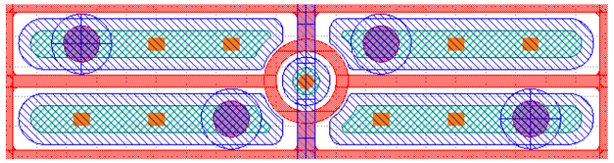
- Similar variants to p-stop

Measurement program will guide design of final sensor!

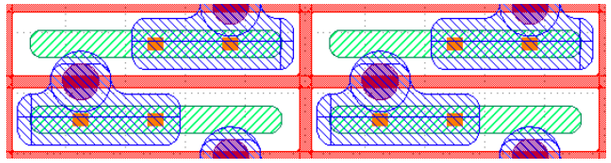
R4S100x25-P1



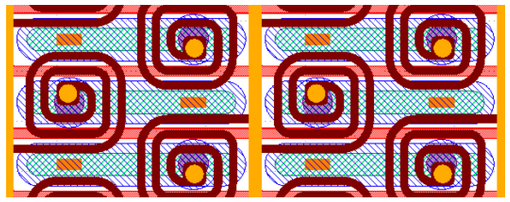
R4S100x25-P2



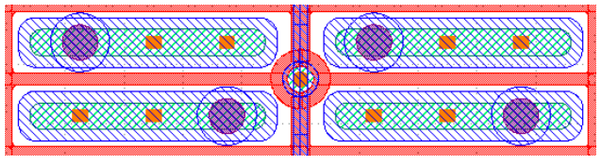
R4S100x25-P4



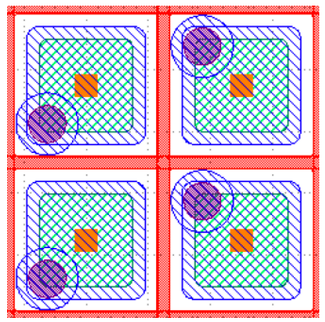
R4S100x25-P6



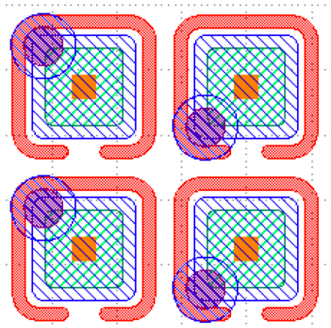
R4S100x25-P8



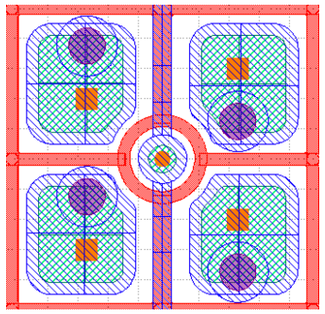
R4S50x50-P1



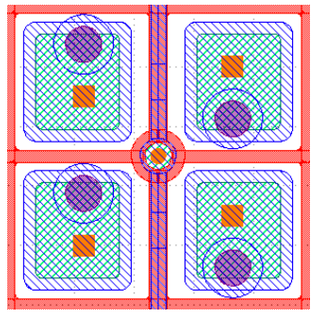
R4S50x50-P2



R4S50x50-P3



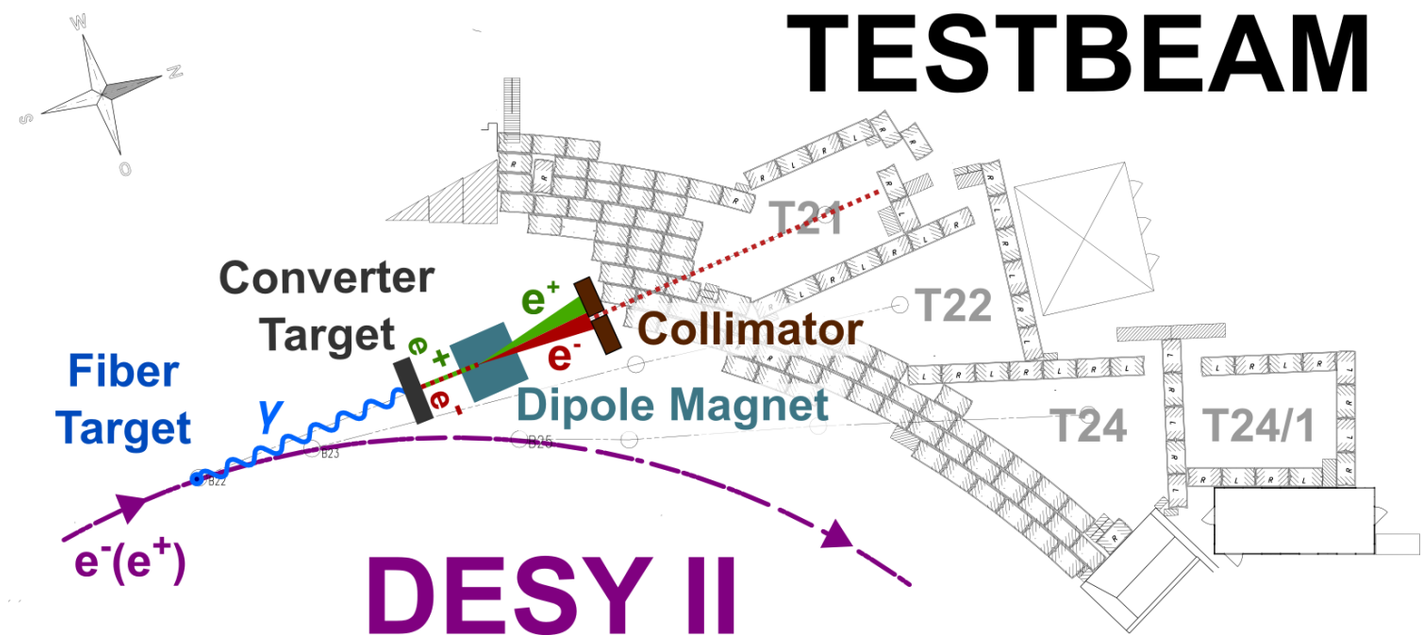
R4S50x50-P9



FIRST DATA FROM DESY TEST BEAM

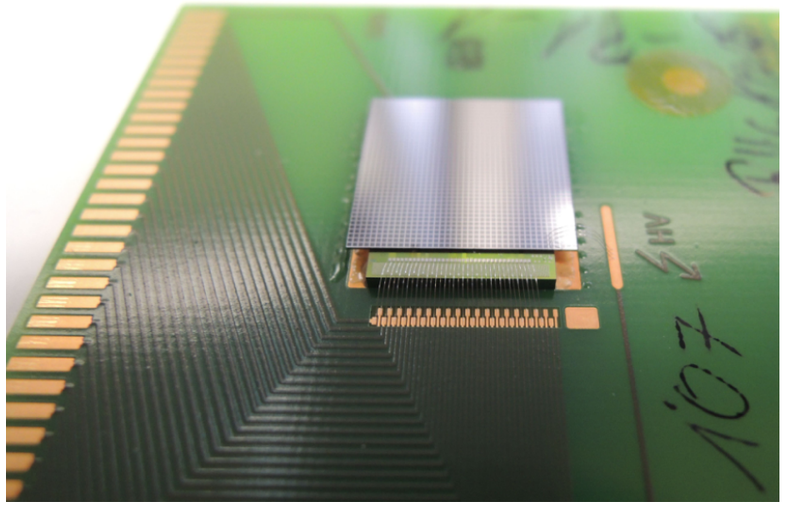
DESY test beam

- Electron / positron synchrotron
- Radius r = 46.6 m
- Injector for DORIS and PETRA
- And for beam test measurements
- Beam on carbon fiber targets
  ➡ Bremsstrahlung
- Bremsstrahlung on copper target
  ➡ electron / positron beam
- Energies from 1 to 6 GeV
- Peak rates around 10 kHz
- Beamline 21
- Setups:
  - EUDET telescope DATURA
  - 3 CMS pixel modules in “Three-master” configuration
  - Edge on configuration

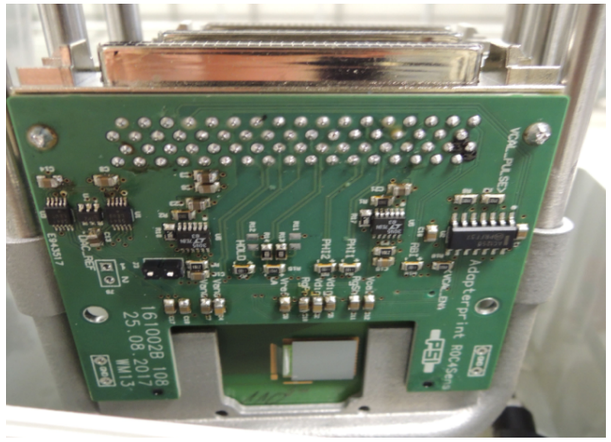


SETUP

R4S with sensor on carrier PCB



Adapter PCB from PSI



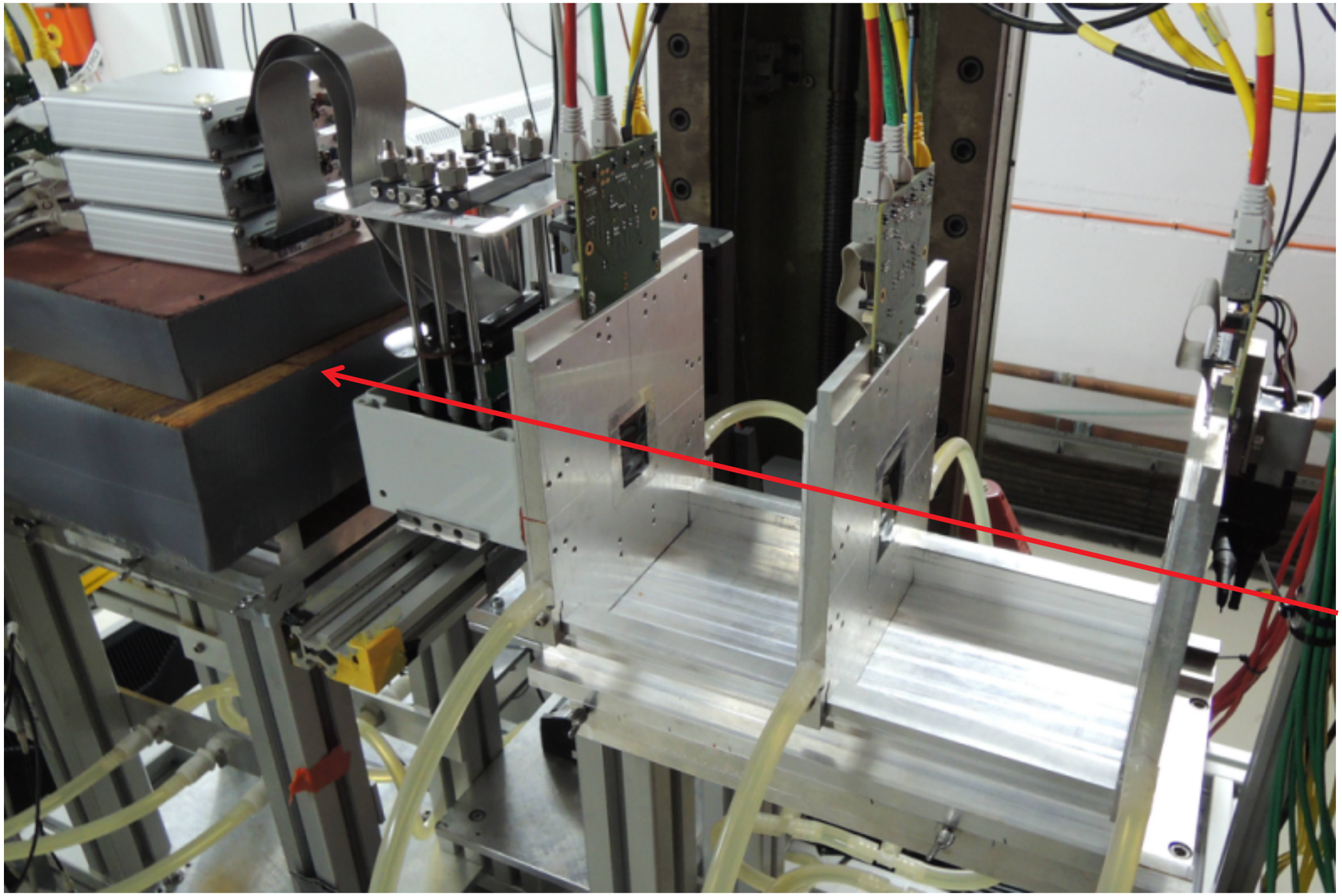
design / production by C. Muhl (DESY)

Three-master:

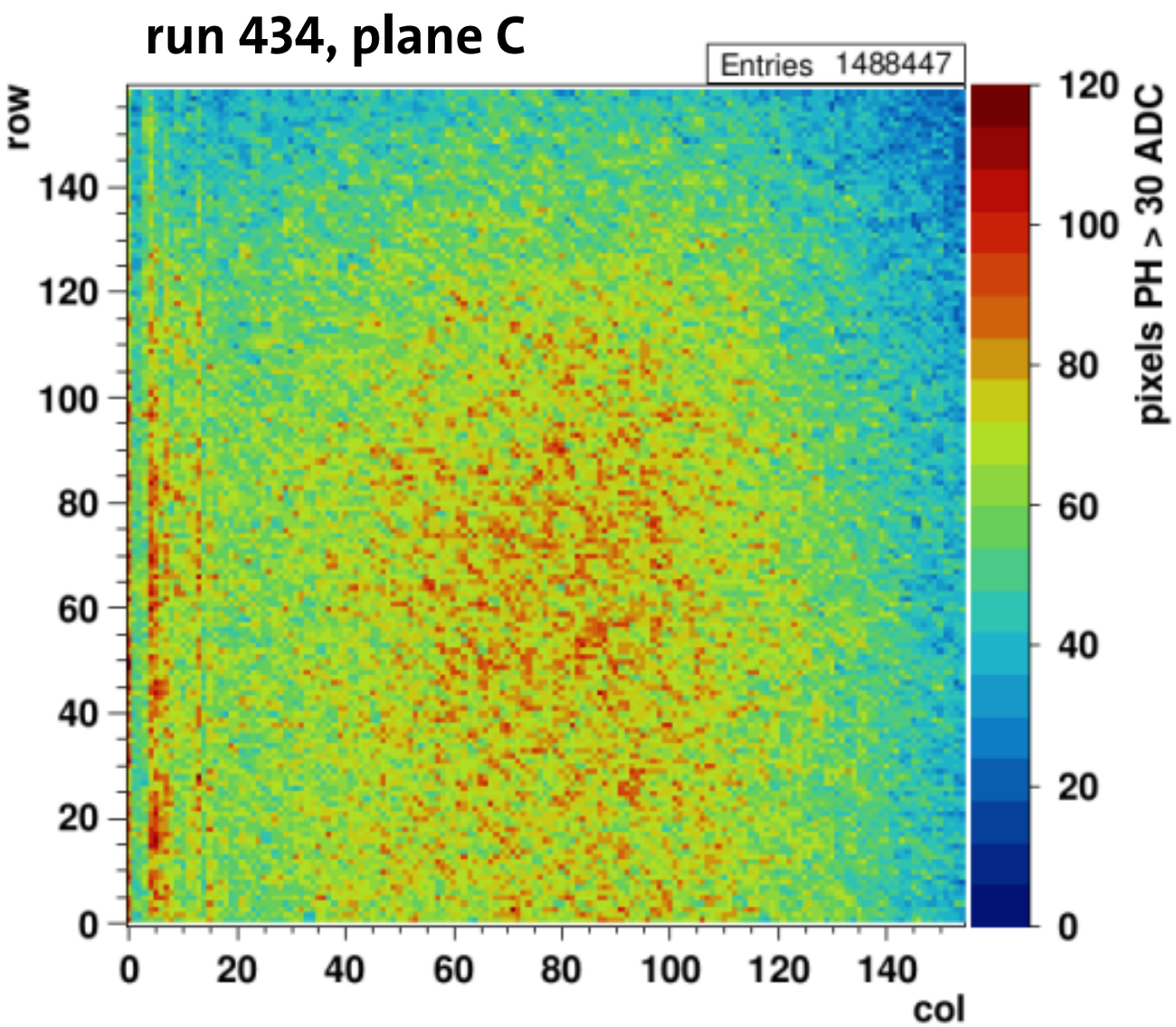
- Support frame for 3 planes
- 20 mm spacing
- Allows reco of tracks with stand alone DAQ / no sync to external device
- Turn angle from 0° to 30°
- With cooling (not used so far)
- Changing sensors takes ~30 min

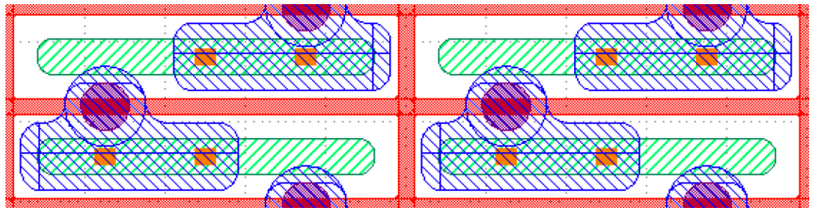
SETUP

Three-master in telescope



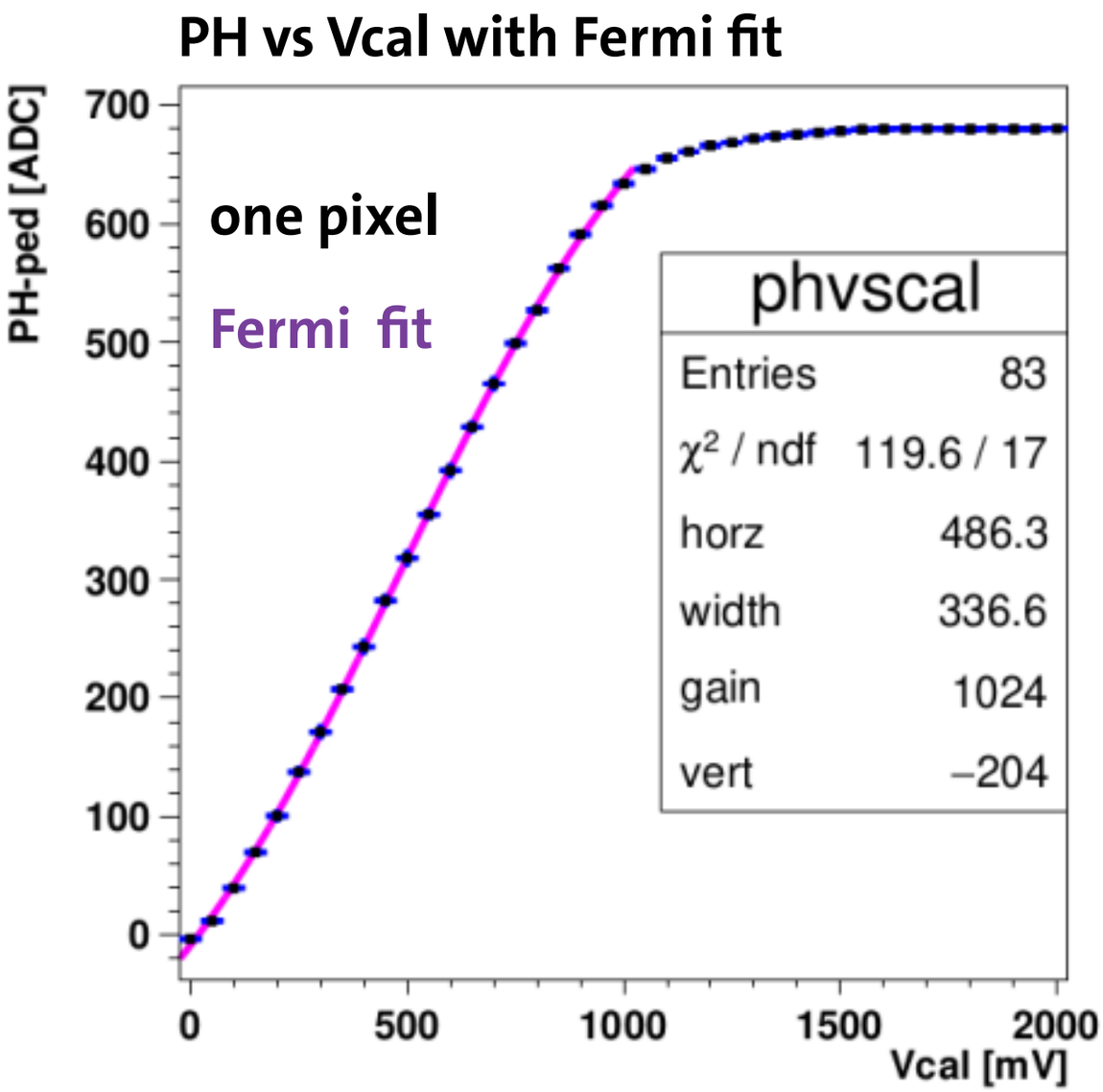
HIT MAP





- Module 114
- FTH150P-R4S100x25-P4
- 5.6 GeV
- Bias voltage: 120V
- At room temperature
- **No bump bond defects**
- Profile due to collimator and/or scintillator

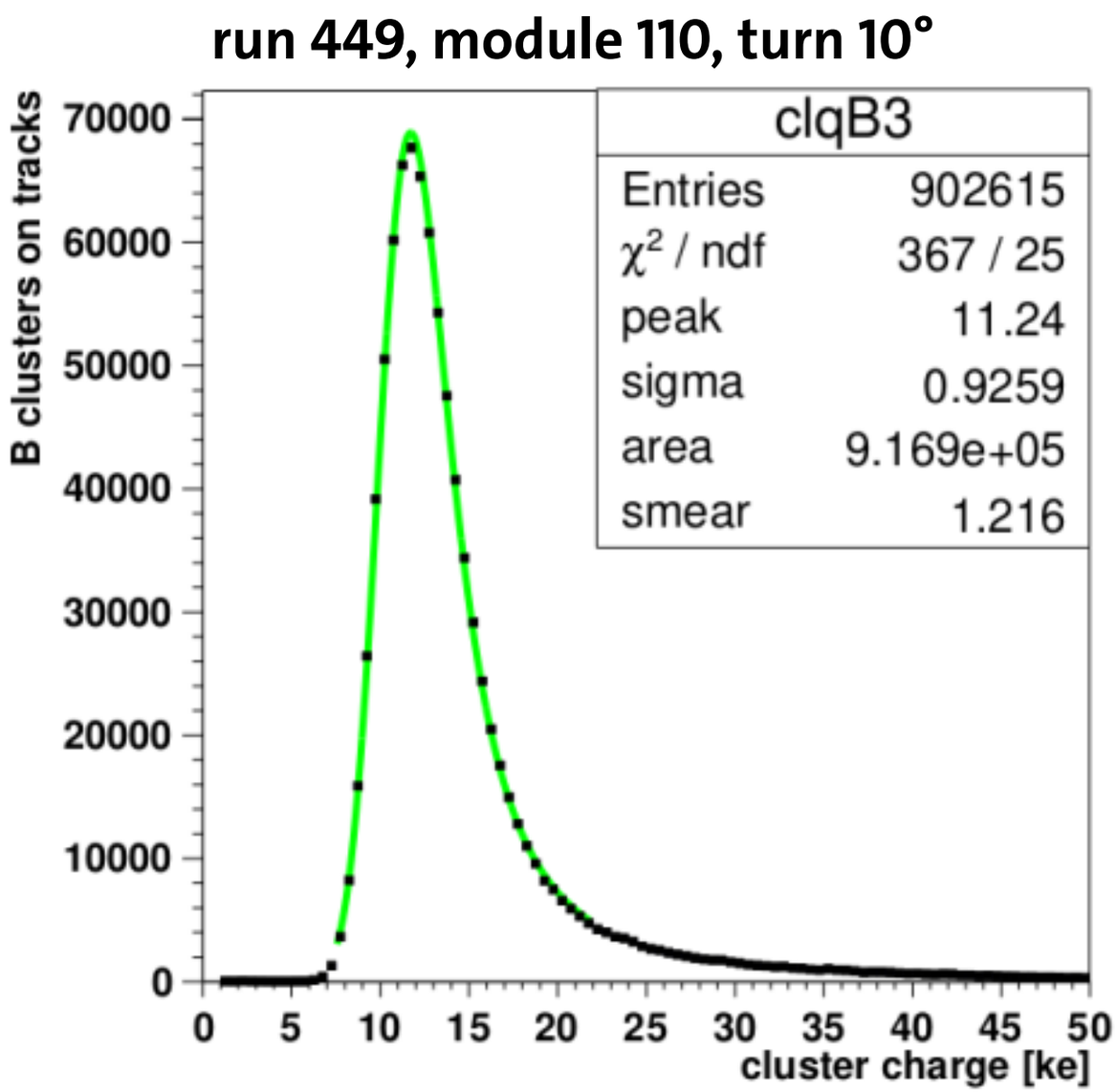
GAIN

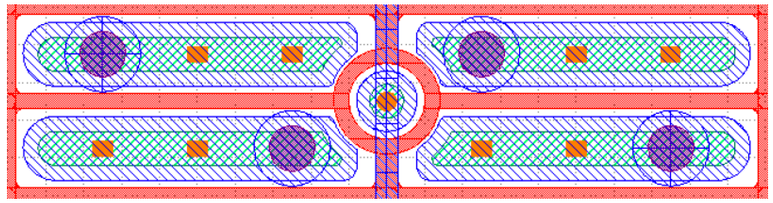


$$PH = p_3 + \frac{p_2}{1+\exp(-u)},\ u = \frac{V - p_0}{p_1}$$

- Gain calibration:
  - Pulse hight vs test pulse
- Fit by Fermi function
  - 4 parameters
  - Good, not perfect
  - Restricted range (Landau peak is at PH-ped = 180 ADC
  - For every pixel

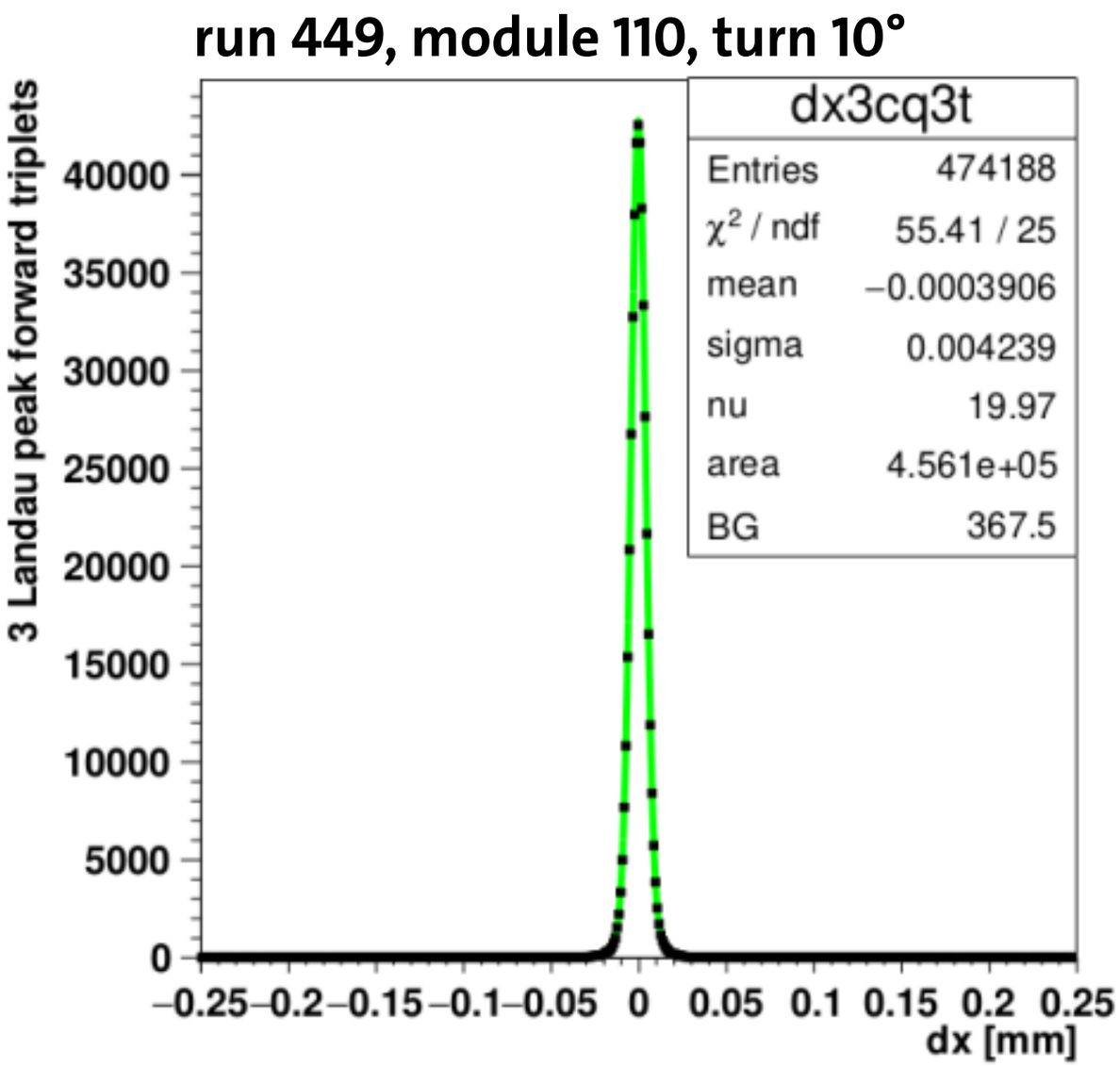
CLUSTER CHARGE

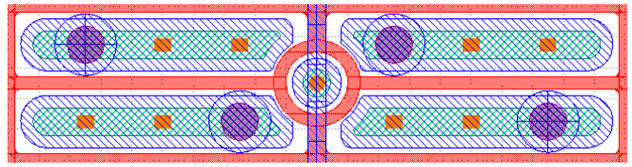


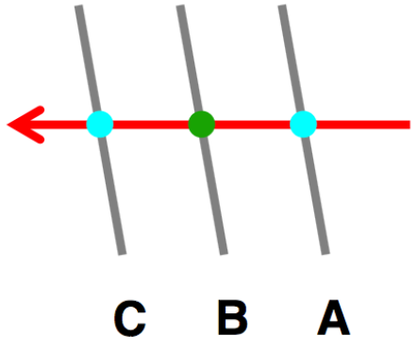


- Module 110
- FTH150P-R4S100x25-P2
- 5.6 GeV
- Bias voltage: 120V
- At room temperature
- Turn angle 10°
- Charge of clusters on tracks
- Offline threshold at 1.4 ke
- Fermi gain calibration
- Scaled to get peak at 11 ke
- Fit by Landau⊗Gauss

TRIPLET RESIDUALS







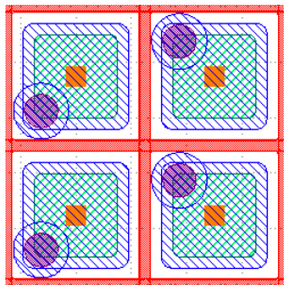
- Module 110
- FTH150P-R4S100x25-P2
- 5.6 GeV
- Bias voltage: 120V
- Turn angle 10°
- Landau peak clusters (8 ke < Q_0 < 16 ke)
- Triplet residuals:

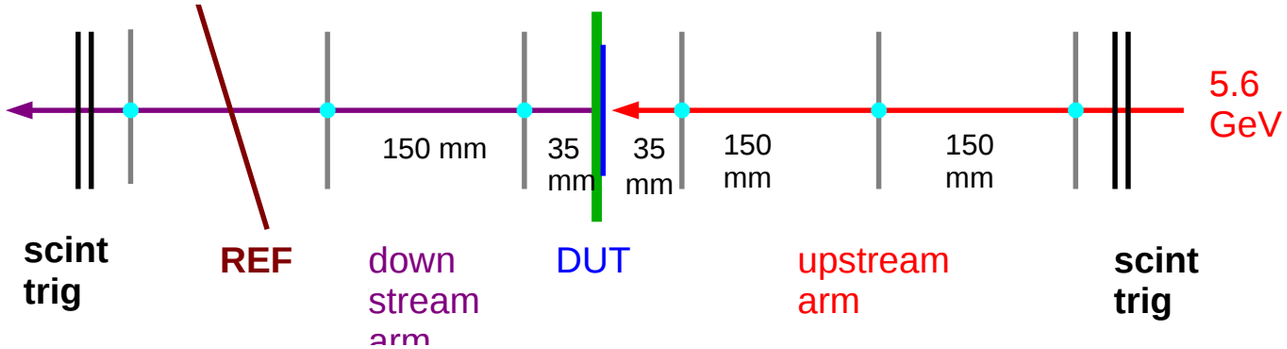
$$\Delta x = x_B - \frac{x_A + x_C}{2}$$

- Plane B residual width = **4.2 µm** in 25 µm direction (fit Student t)
- Unfolding other planes and multiple scattering: **2.7 µm** (binary 7.2 µm)
- Using PCB with cutout: **2.0 µm** after unfolding

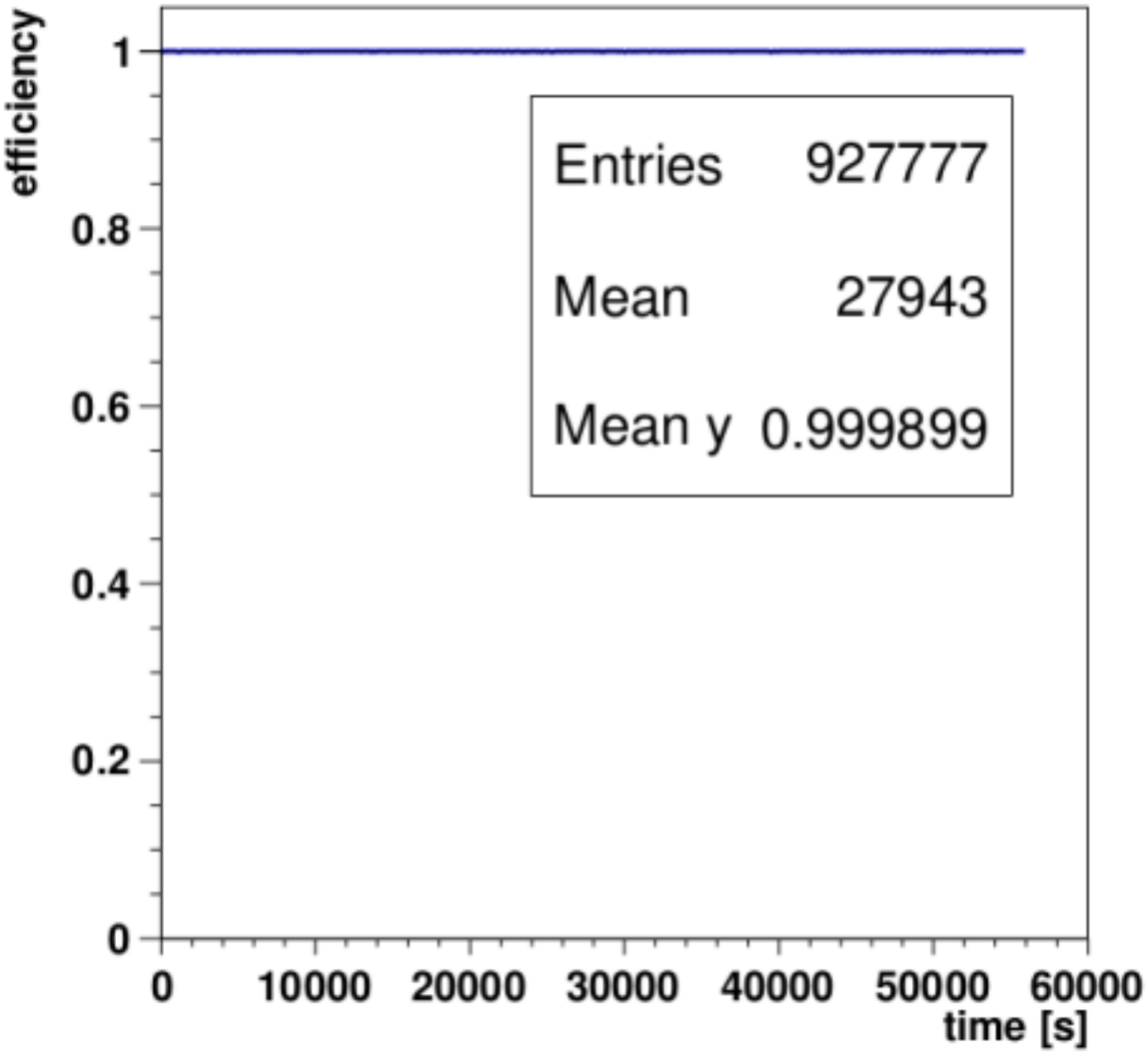
HIT EFFICIENCY

R4S50x50-P1:





run 31168, module 117, turn 0°



$$Efficiency = \frac{N(Hit)}{N(Track)}$$

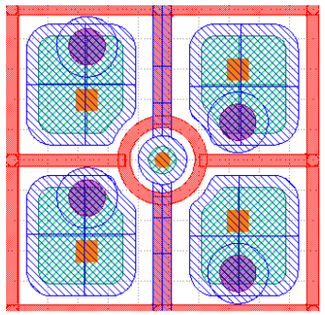
- Track definition:
  - Get **upstream** and **downstream** triplets
  - Match triplets using tight 0.1 mm cut
  - Demand REF-link; tight 0.1 mm cut
  - Demand 0.6 isolation at REF
- Hit definition (hit on track):
  - Take Track
  - Demand DUT-link; loose 0.3mm cut
- Fiducial region 0.2 mm to sensor edge

➡ **Flat at 99.99% over 15 hours**

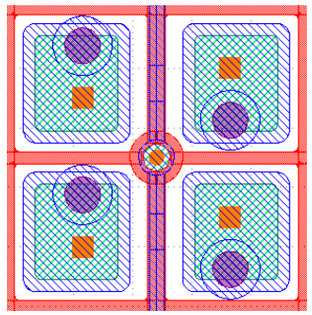
IN-PIXEL CHARGE COLLECTION

Small vs large bias dot for normal incidence

R4S50x50-P3

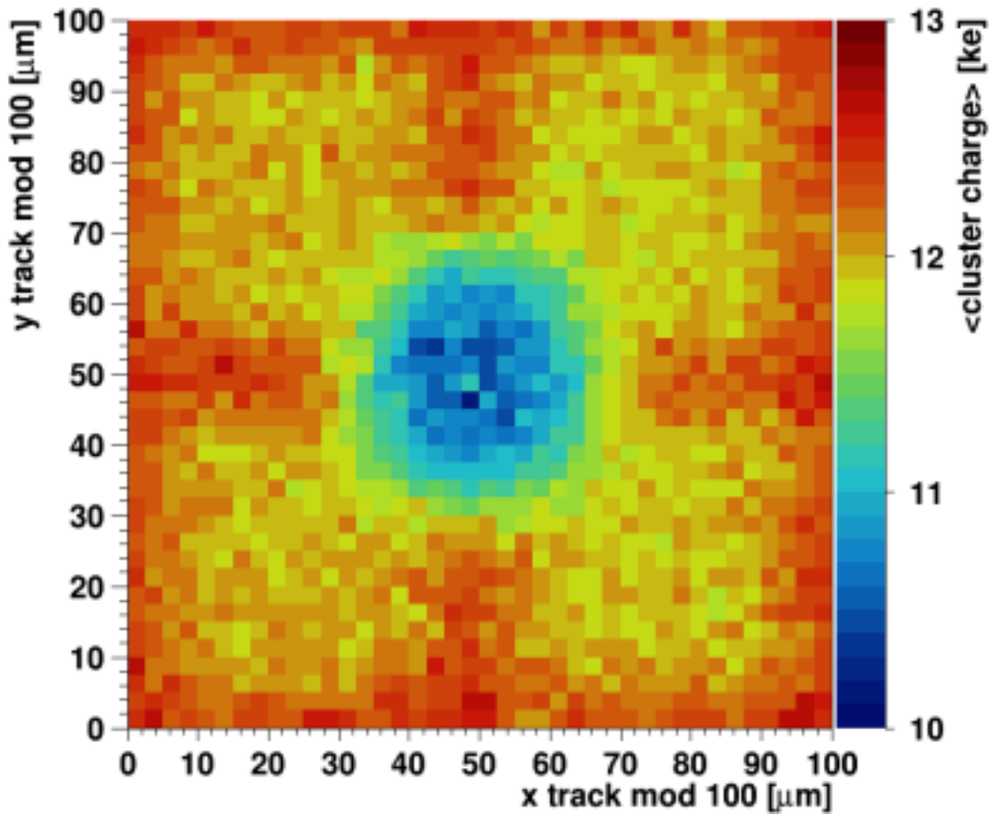


R4S50x50-P9

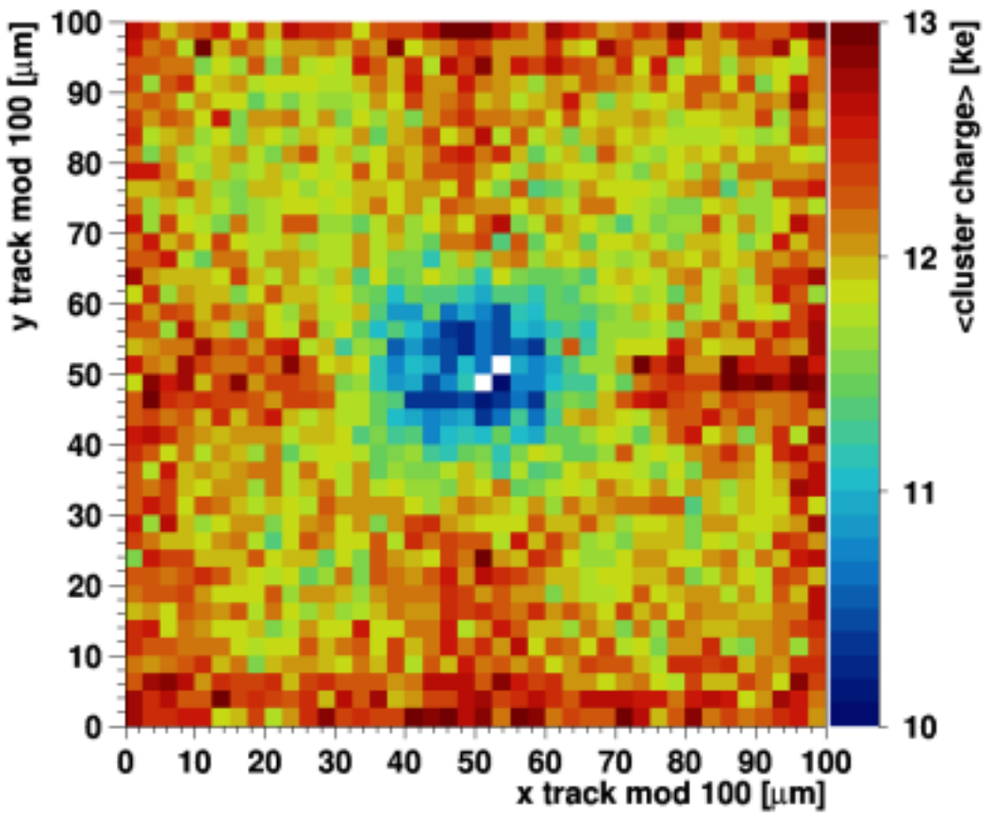


Design suggested by Y. Unno

run 31393, module 102, turn 0°



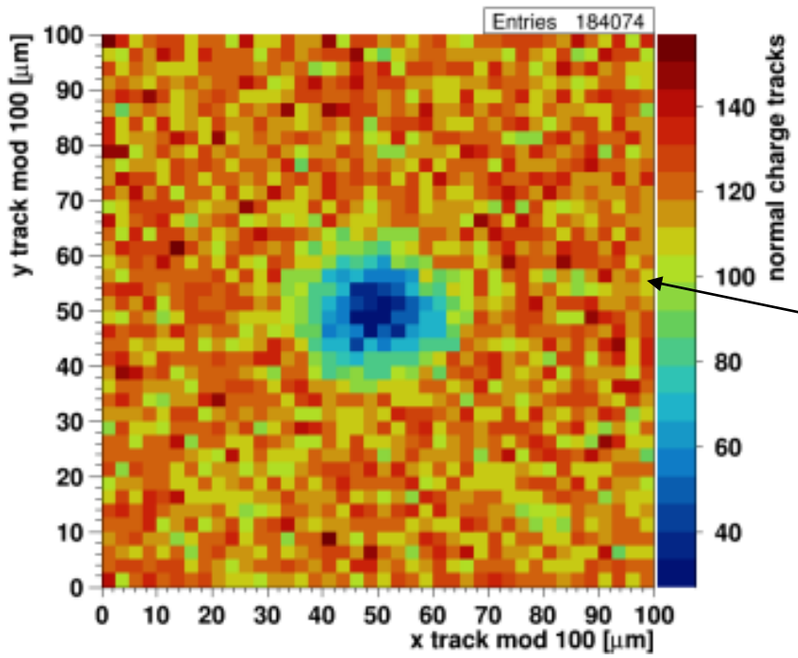
run 31315, module 142, turn 0°

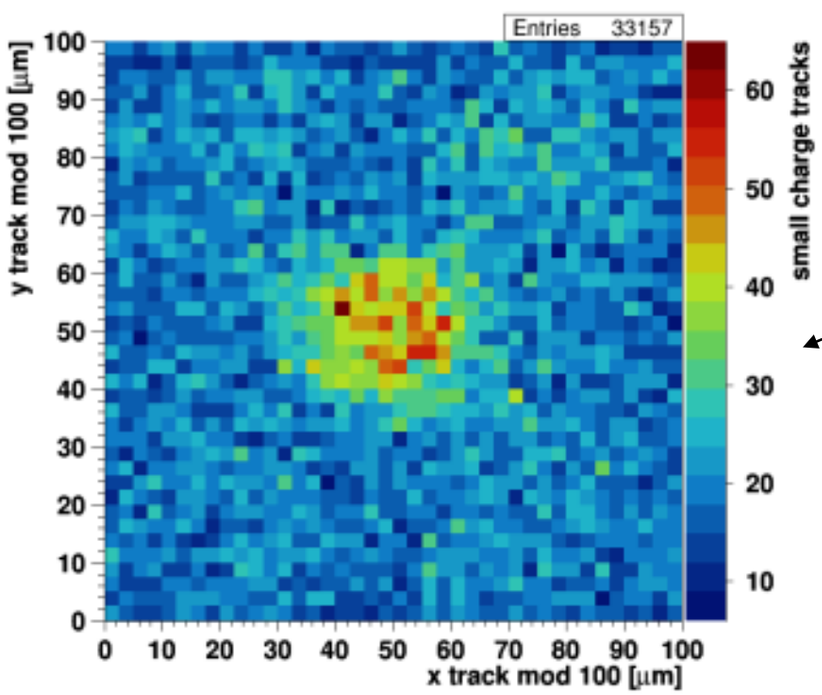


Large bias dot (d = 25 µm) leads to large area with low cluster charge

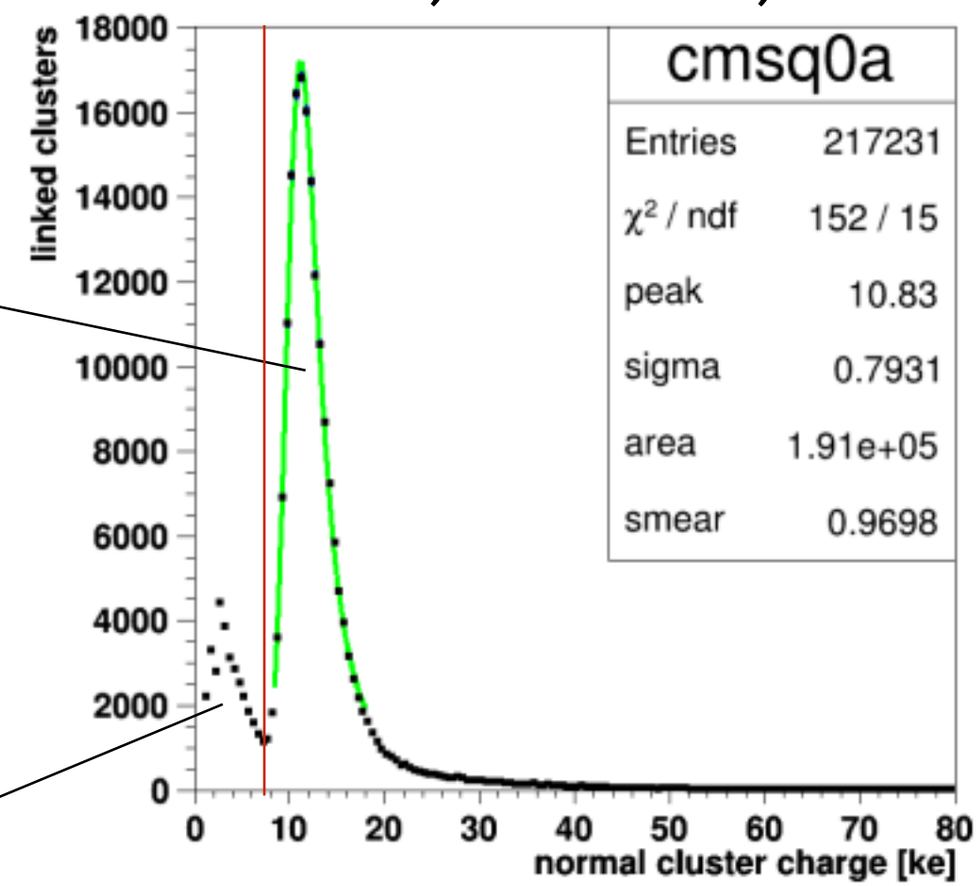
IN-PIXEL CHARGE COLLECTION

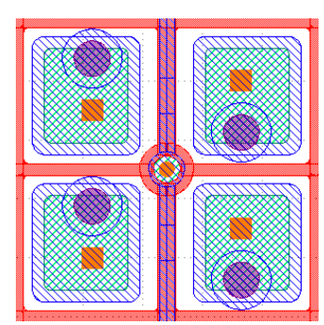
Reduced bias dot: cluster charge





run 31315, module 142, turn 0°



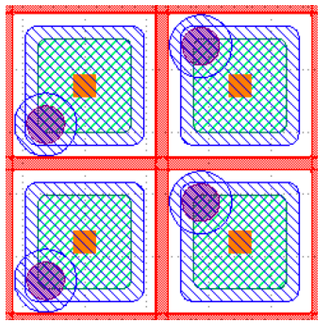


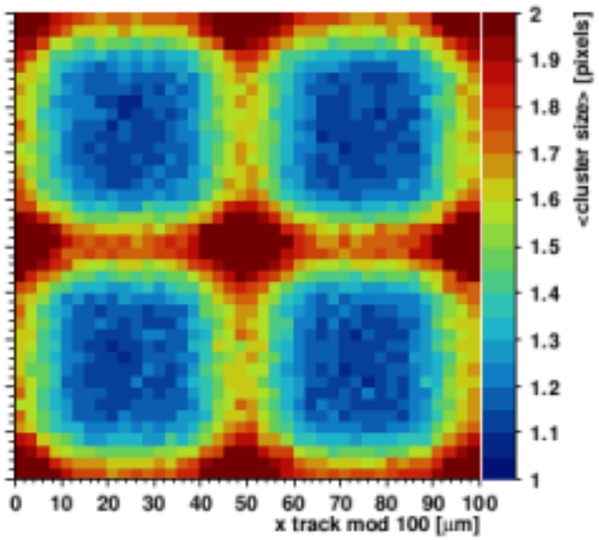
- Module 142
- FTH150P-R4S50x50-P9
- Bias voltage: 120V

IN-PIXEL CHARGE COLLECTION

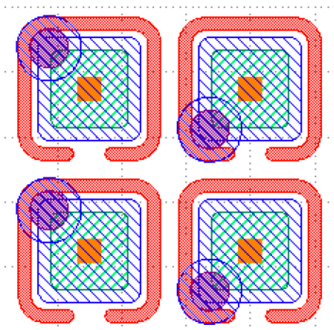
Cluster size vs. track impact point

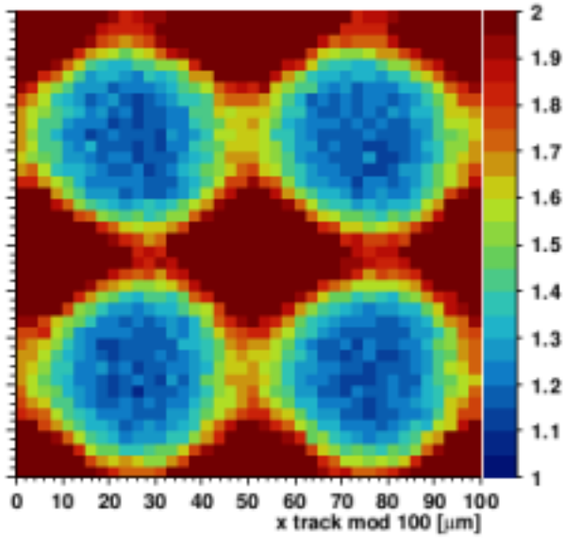
R4S50x50-P1



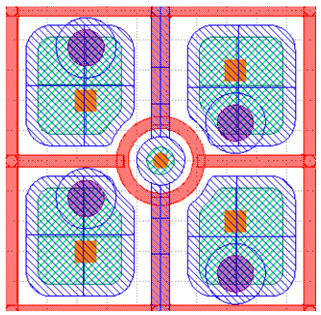


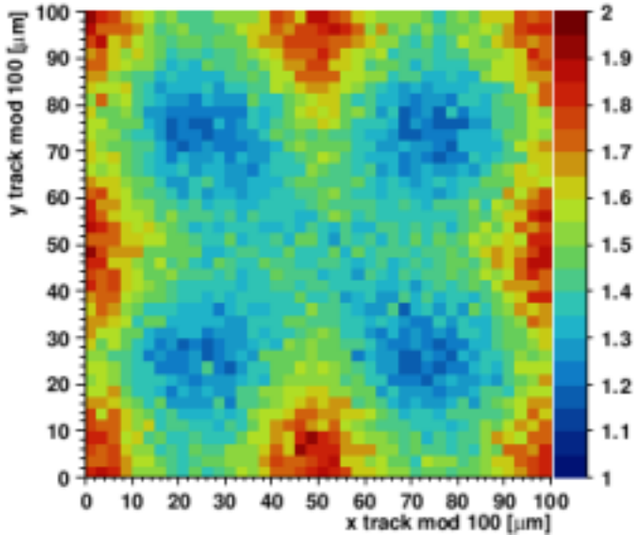
R4S50x50-P2





R4S50x50-P3





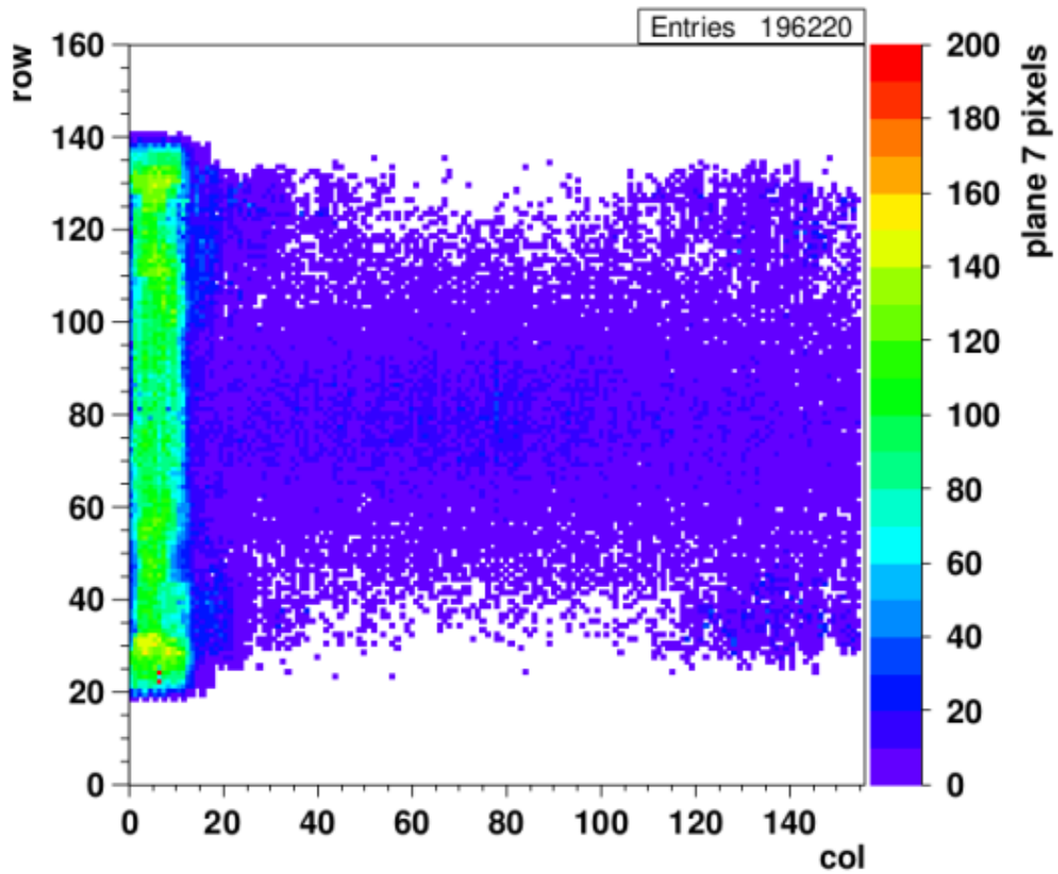
- Bias voltage: 120V
- Normal incidence
- 5.6 GeV
- Using beam telescope

- Cluster size determined by diffusion and field distribution
- Bias scans for further investigations

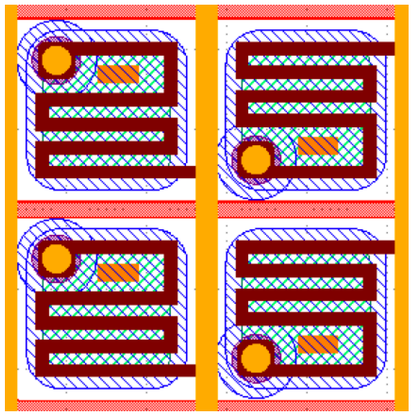
POLY SILICON BIAS SENSOR

Hit map

run 31126, module 106, turn 0°

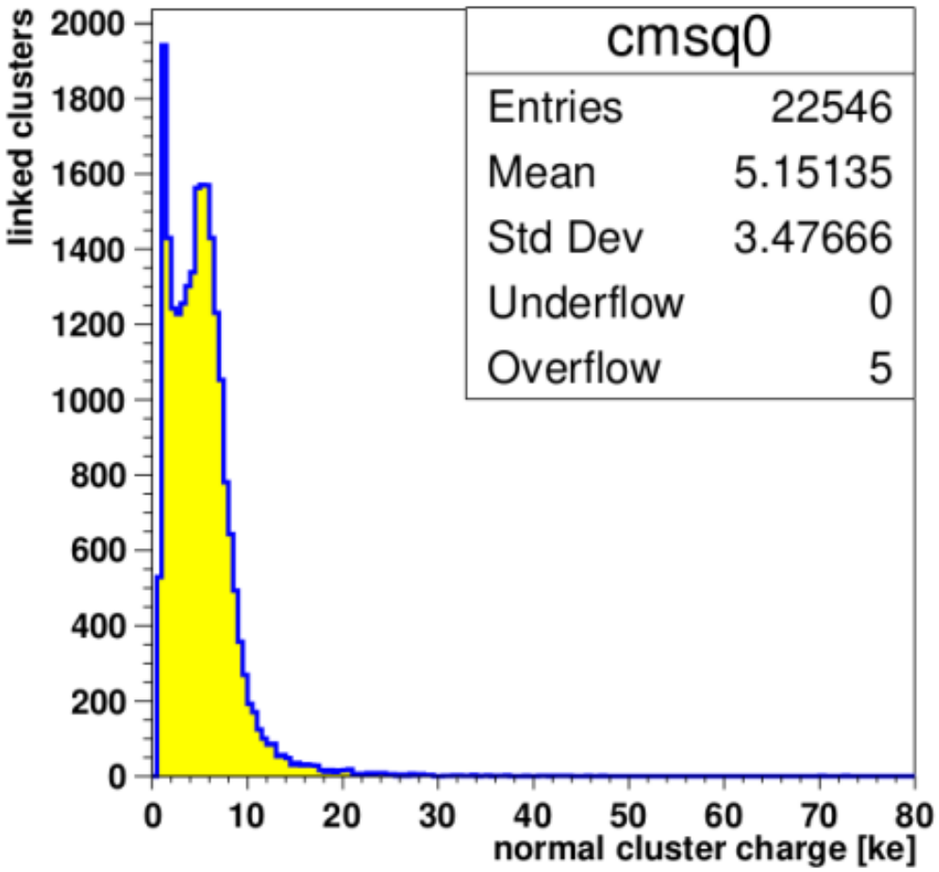


R4S50x50-P6



Cluster charge

run 31126, module 106, turn 0°



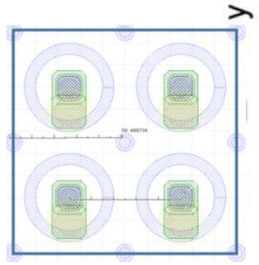
- Bias voltage: 120V
- First 15 columns are noisy
- Lower 20 and upper 20 rows no signal
- Only central band of rows is efficient

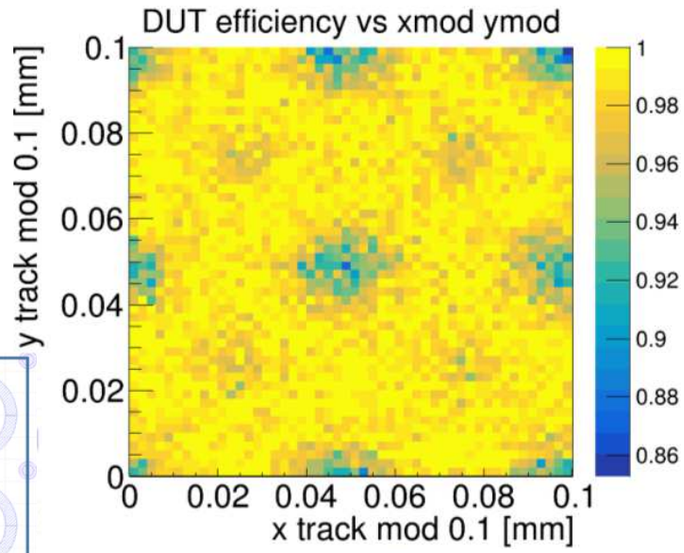
- Bias voltage: 120V
- Cluster on track
- Peak at 5 ke
- Expected 11 ke from sensor thickness

➡ **Further investigations needed! Uniformity of resistors?**

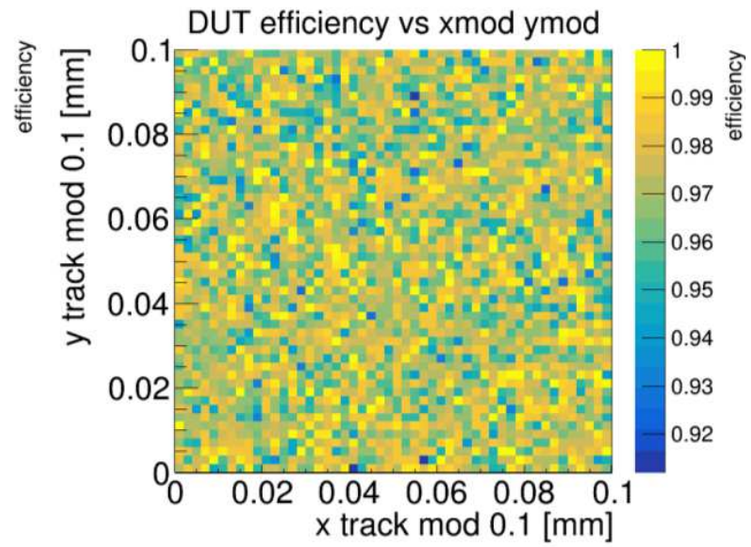
CMS 3D PIXEL SENSORS

Resolution studies@DESY test beam (5.6 GeV)



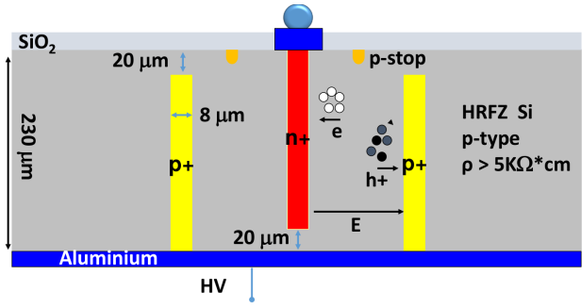


turn 0°

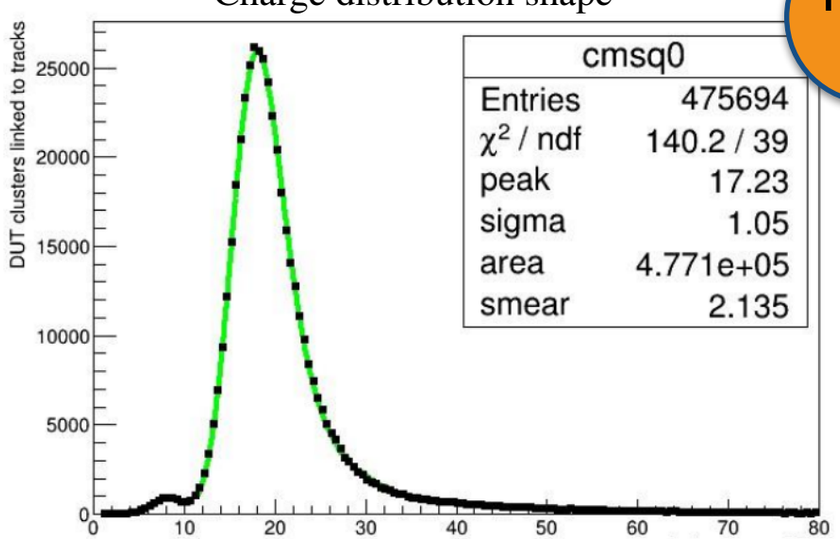


turn 12°

CNM, Barcelona
Double sided 3D process
50x50 µm²
BB at IZM to ROC4Sens



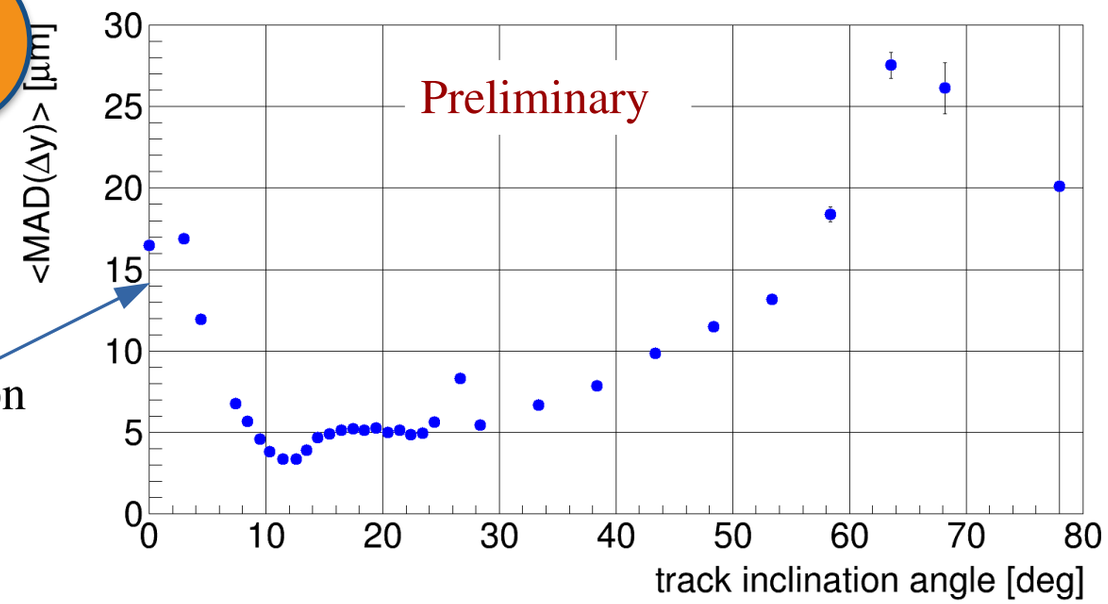
Charge distribution shape



a.u.

First small pixel 3D in CMS

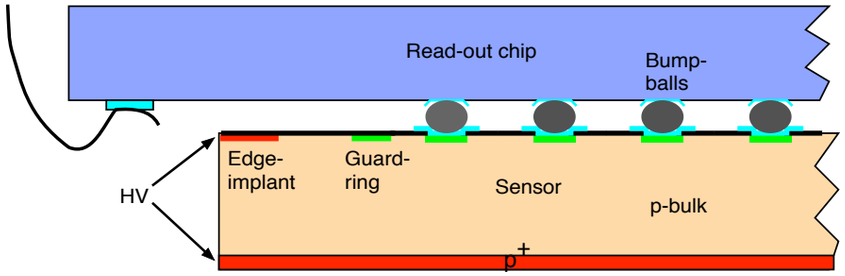
Binary resolution



HPK SUBMISSION: SPARKING

Options for spark protection:

- BCB on sensor, on chip or on both
- Parylene

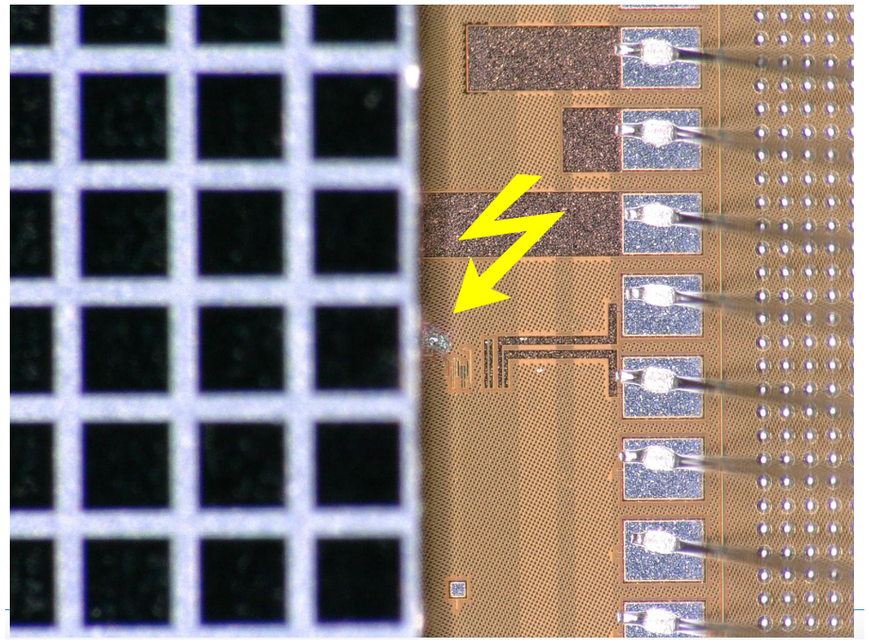


First attempt at IZM:

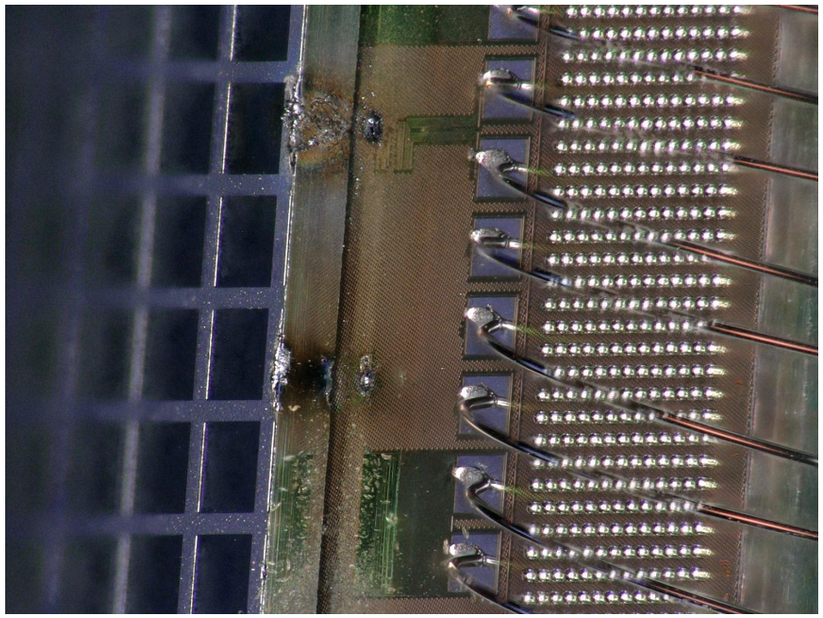
- BCB on sensor only (frame only)

➡ Sparking at approx. 490 V observed (Paschen's Law gives for a gap of 25 µm: 495 V)

Module 106- Top-view



Module 112 - Side-view



- ROC4Sens has additional test pads close to the sensor (not in PROC600/PSI49)

➡ Next iteration with BCB on sensor and chip

SUMMARY

New pixel detector for HL-LHC:

- Extend forward coverage up to |η| = 4
- Small pixel, thin, rad. hard sensors
- RD53: Development of radiation hard, small pixel size ROC in 65 nm technology

R&D programs with in CMS:

- Thin, small pitch planar pixel sensors
  - HPK submission, INFN/FBK
- 3D pixel sensors
  - INFN/FPK, CNM Barcelona

HPK submission:

- First thin sensors of 50x50 μm^2 and 100x25 μm^2 pixel size successfully bump bonded to novel PSI chip
- First test beam results with ROC4Sens are very promising
  - Resolution for 100x25 μm^2: **2.0 µm** after unfolding
  - Efficiency > 99.99% before irradiation
  - Sensors with poly silicon bias shows some problems
- Irradiated modules expected back from CERN during these days

➡ Many studies ahead of us to guide final design of sensors

- Bump bonding of RD53A and tests will be started beginning of next year

Backup