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Planar pixel sensor development for the CMS Phase II upgrade

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INTRODUCTION

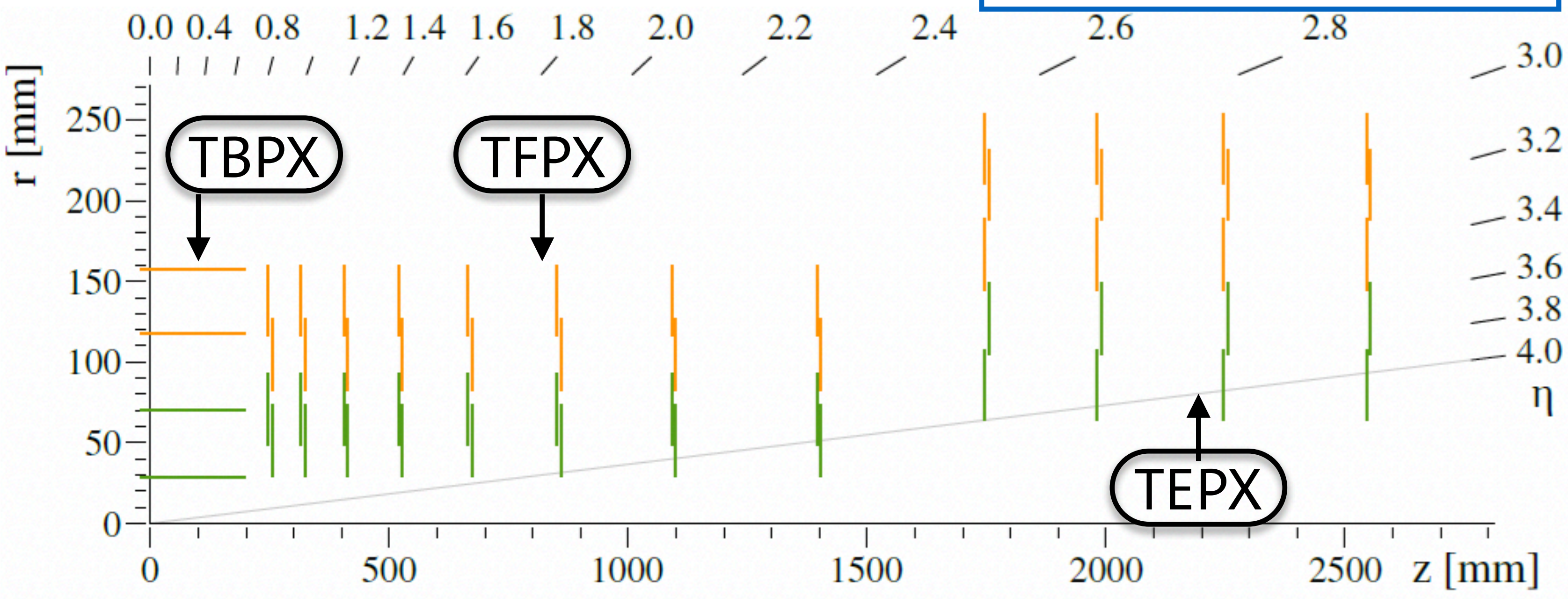
High-Luminosity LHC :

- 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)

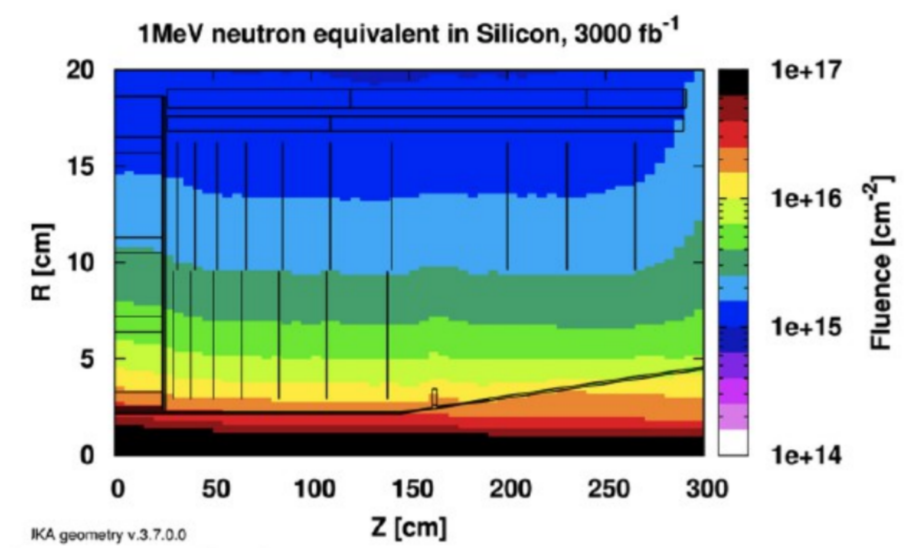
Pixel layout:

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

Layer	Φ_{eq} [10^{16}cm^{-2}]
L1	2.3
L2	0.5
L3	0.2
L4	0.15

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

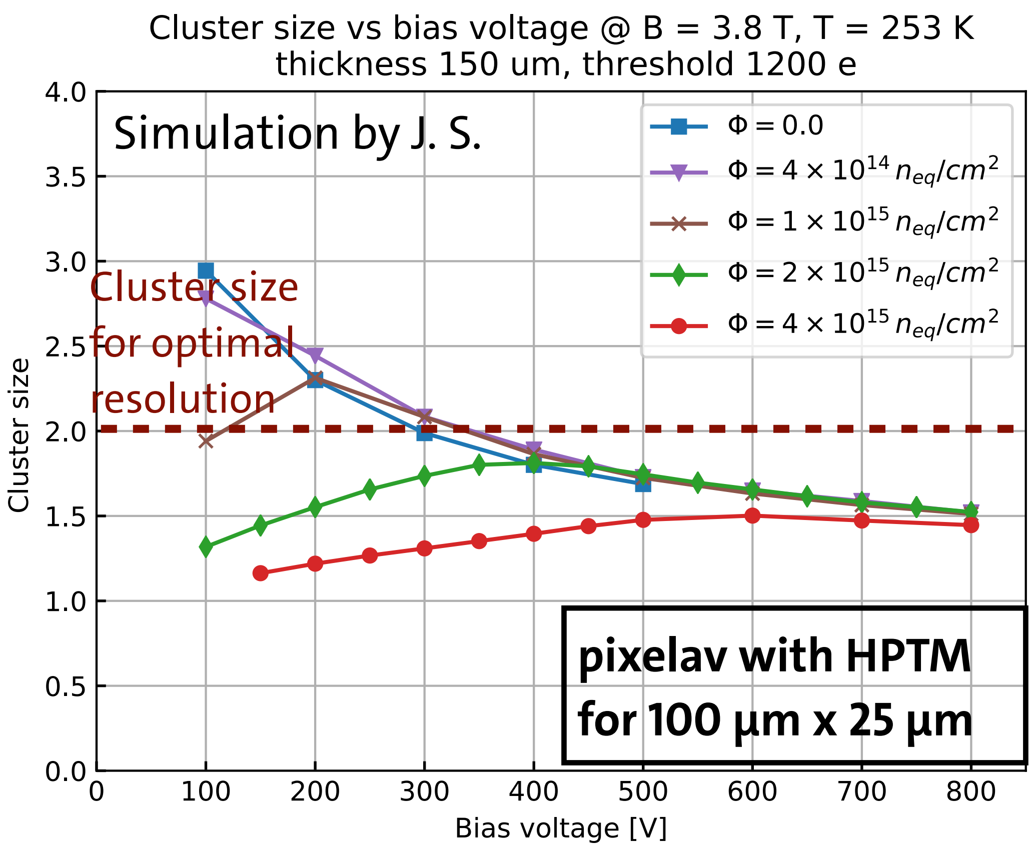
- R&D in parallel. Both options described and costed in TDR.

SENSOR REQUIREMENTS

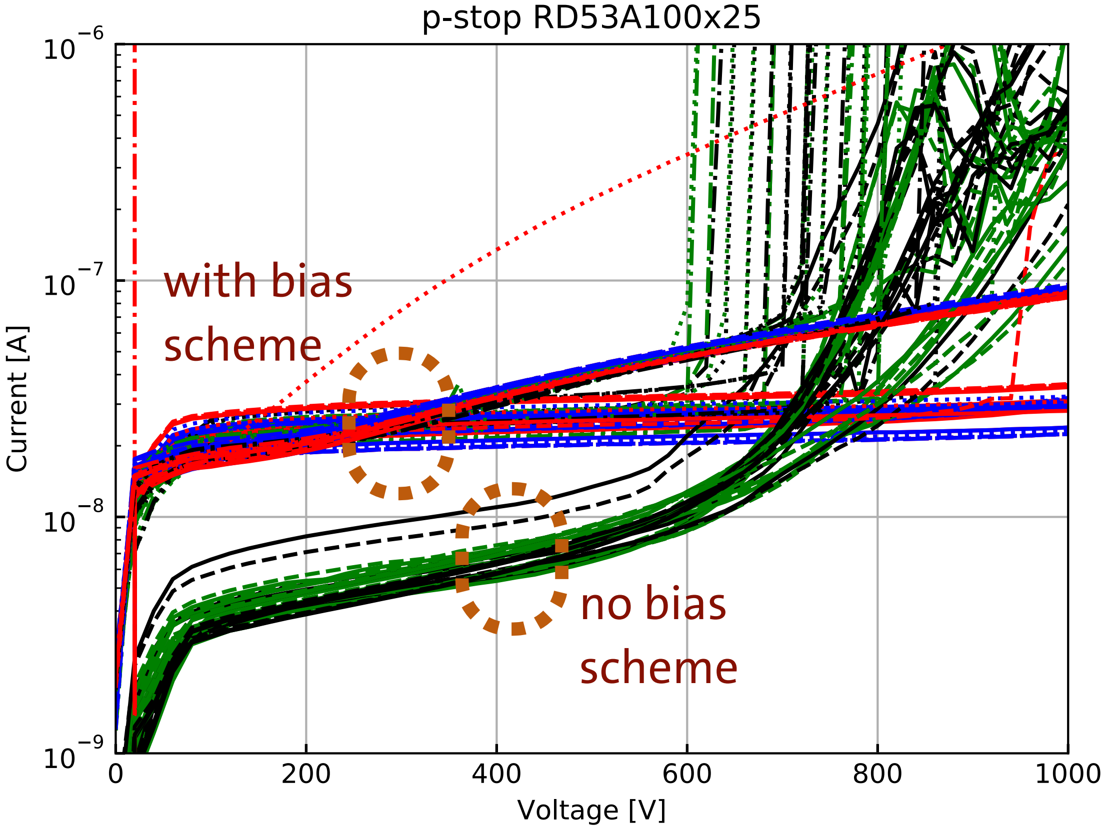
Operational voltage:

- Before irradiation and for fluences up to $1\times10^{15}\,n_{eq}/cm^2$ for an optimal resolution in a 3.8 T B-Field with low threshold

➡ 300 - 400 V are required for 150 µm thick sensors



I-V of HPK RD53A sensors



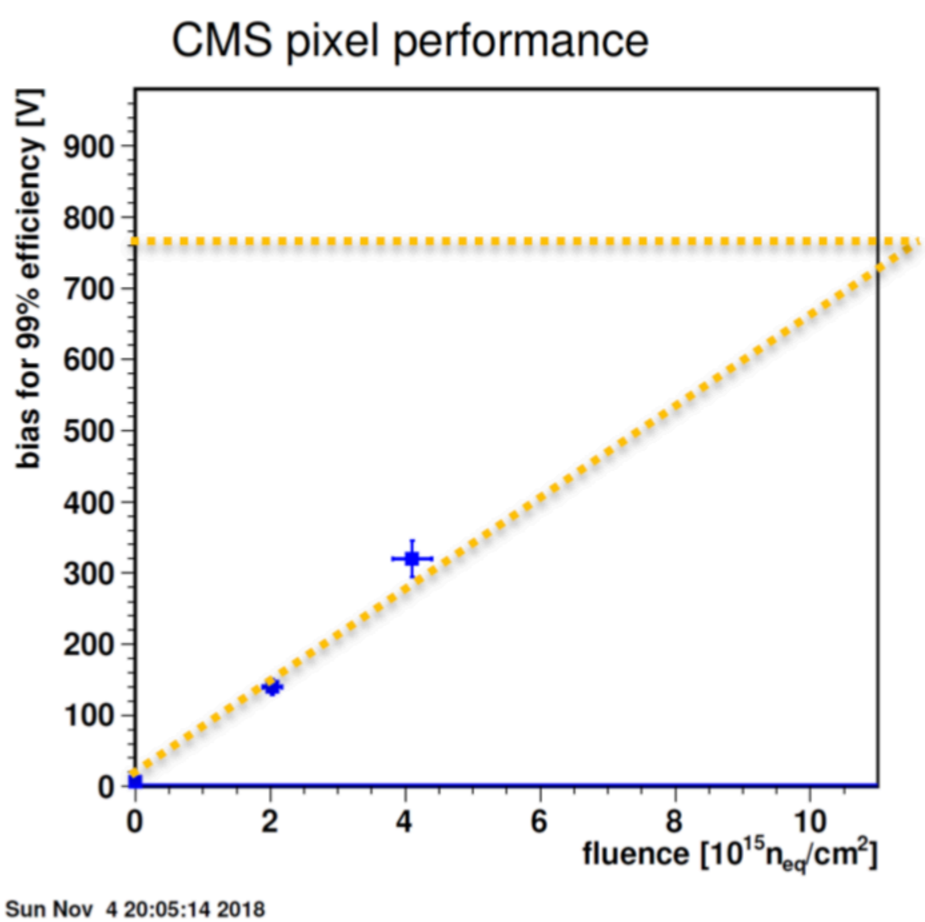
➡ Breakdown voltage > 600 V

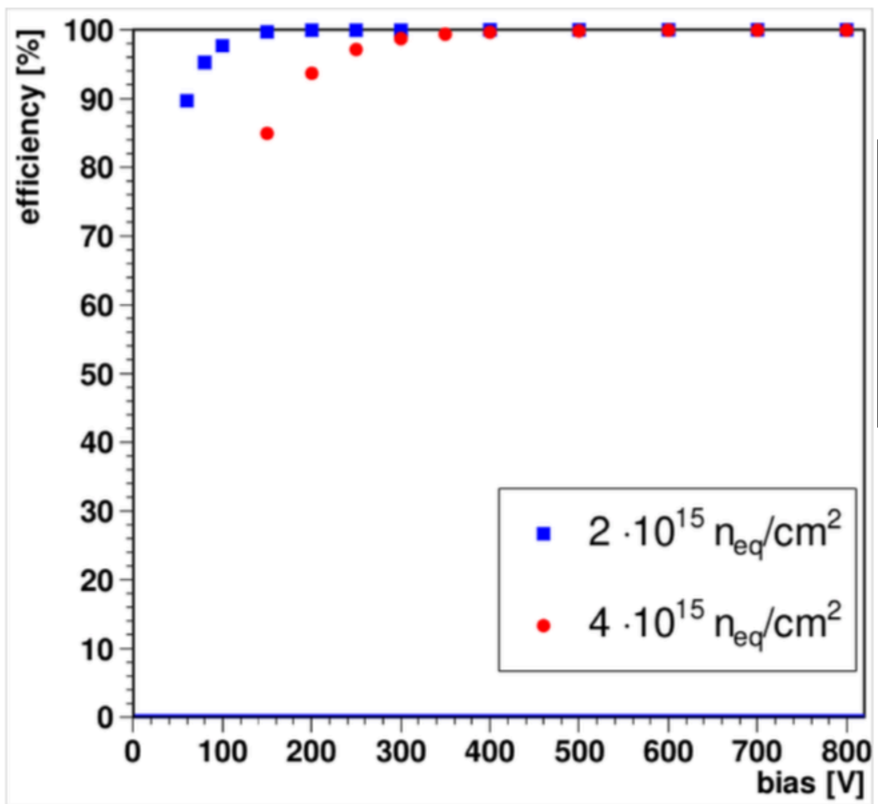
➡ No problem for HPK sensors

SENSOR REQUIREMENTS

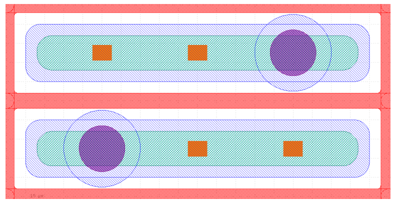
Efficiency after irradiation for track reconstruction with 3 out of 4 hits should be > 99.9%:

- Maintain efficiency > 99% for voltages < 800 V at $\Phi_{eq} \approx 5x10^{15}\ cm^{-2}$ (Layer 2)
- Maintain efficiency > 97% for voltages < 800 V at $\Phi_{eq} \approx 1.2x10^{16}\ cm^{-2}$ (0.5x Layer 1)





High bias voltages (~800 V) required to maintain high efficiency at larger fluences



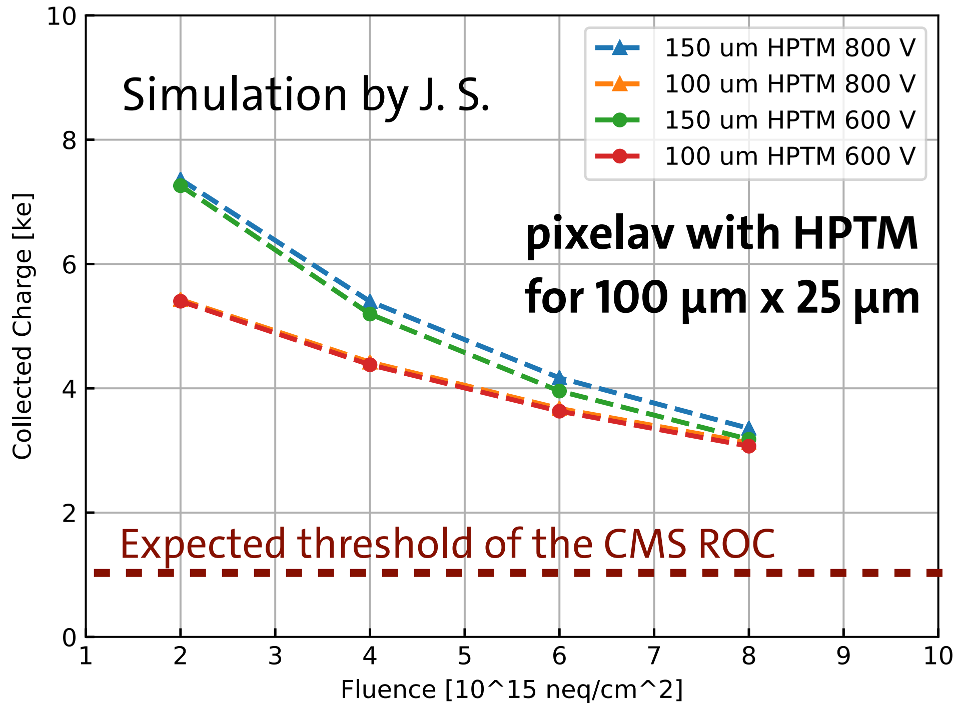
Irradiation study with **ROC4SENS** chip + sensor w/o bias dot

PLANAR R&D WITHIN CMS

Thin, small pitch planar pixel sensors:

- **HPK submission (n^+-p): 150 µm active thickness**
- 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

➡ expected to deliver S/threshold > 3 at up to $\Phi_{eq} \approx 8 \times 10^{15}$ cm^{-2}



Readout chip available for R&D with pixel size 50 µm x 50 µm and 100 µm x 25 µm

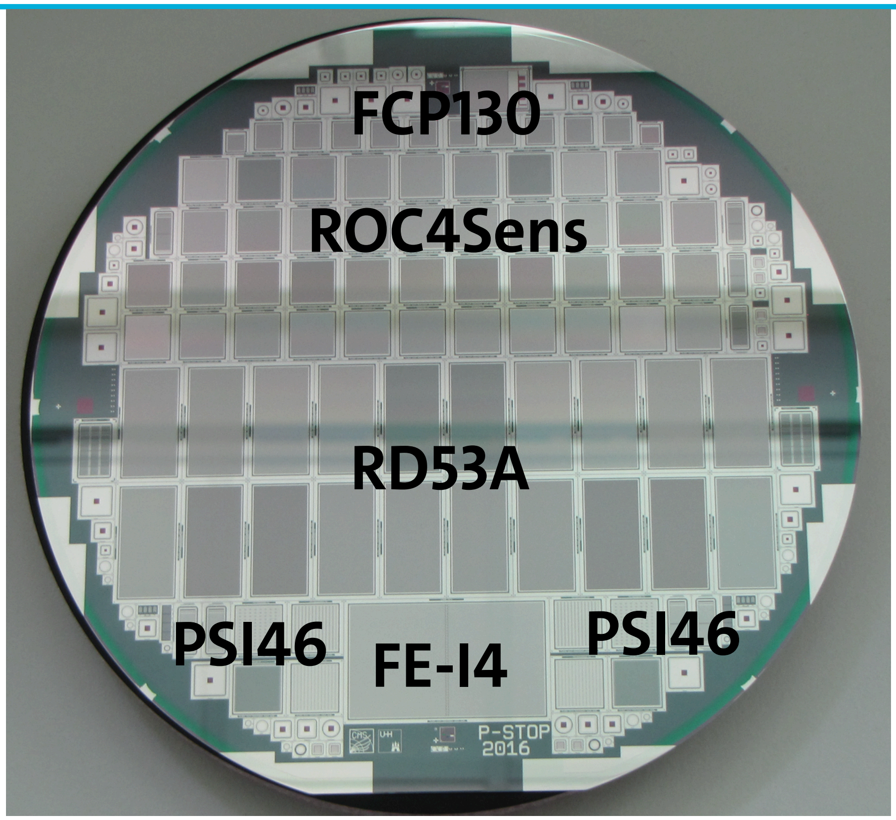
- ROC4Sens (PSI R&D chip available since summer 2017)
- RD53A

HPK SUBMISSION: OVERVIEW

Sensor order:

≈ 2945 sensors + 3400 test structures

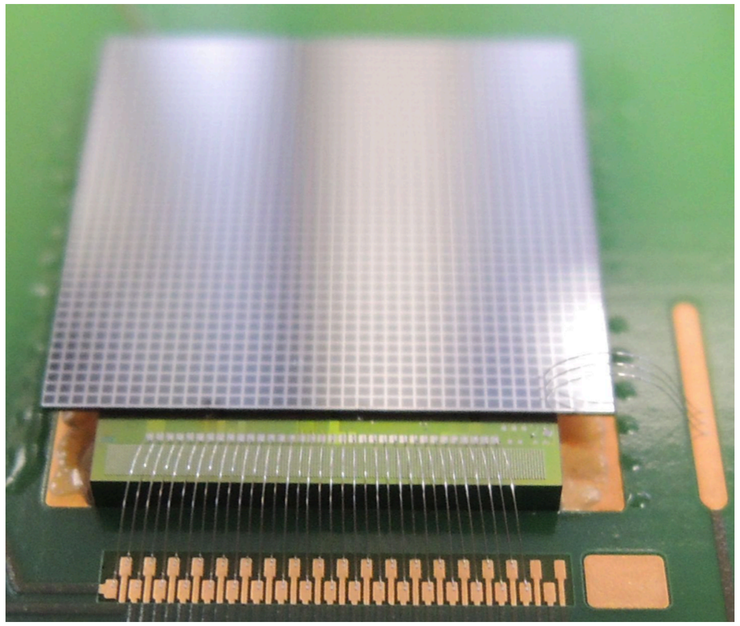
- 35 wafer 6” n^{+}-p FZ
  - 10 wafer with **150 µm thickness** (FTH150)
  - 20 wafer with **150 µm + 50 µm handle wafer** (FDB150)
  - 5 wafer with **150 µm deep diffused** (FDD150)
- Resistivity: 1 kΩ·cm - 5 kΩ·cm
- Isolation: 25 with **p-stop** (P) and 10 with **p-spray** (Y)
- Biasing schema: **none**,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



Bump-bonding:

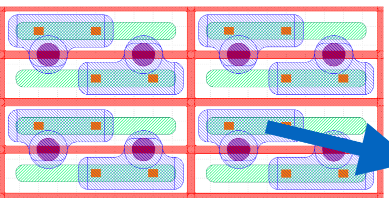
- 8 wafers (2xFDB150P, 2xFTH150P, 2xFDD150P, 2xFTH150Y) have been processed at IZM
- 2 wafers (2x FDB150P) have been processed at RTI
- approx. 130 **ROC4Sens** modules received
- approx. 70 **RD53A** modules received
- + test structures (diodes, MOSFETs, MOS-C, GCDs etc.)

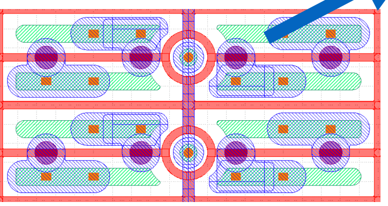
ROC4Sens module



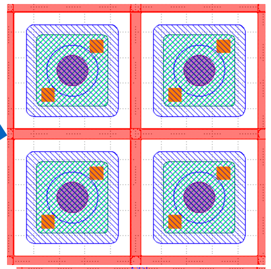
HPK RD53A DESIGN VARIANTS

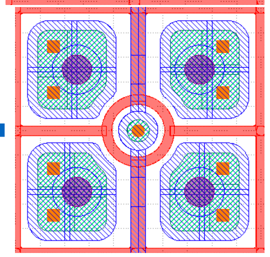
- Streamline plan focuses on **RD53A** compatible sensors
- 3 wafer types -> 2 wafer types: FTH150, FDB150, ~~FDD150~~ (no deep diffused)
- **In bold: sensors considered in high priority plan**

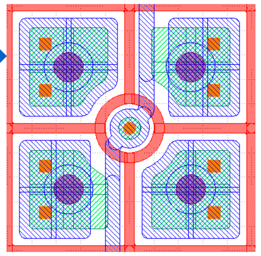




	25x100 mm^2		50x50 mm^2
P1	**no bias**	**5P1**	**no bias**
P2	**common punch through**	5P2	(open p-stop)
P3	poly Si	**5P3**	**common punch through, straight**
P4	-	**5P4**	**common punch through, wiggle**
P5	poly Si	P5	poly Si
P6	-	P6	poly Si







- Similar sensors for **p-spray**, evaluated with somewhat lower priority
- Designs with polysilicon resistors showed problems for the ROC4Sens

➡ Not considered in the streamline plan for the RD53A

DEFINE PIXEL CELL

Irradiation and measurement program on small pitch sensor modules

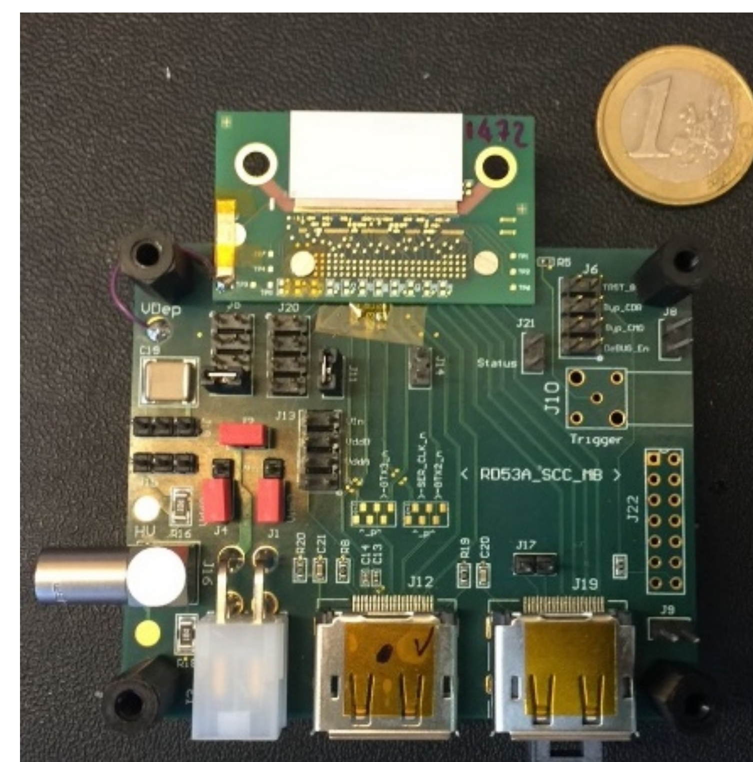
- Irradiate small-pitch hybrids at CERN (24 GeV/c p)[1)], LANL, KIT (23 MeV p)[1)] and JSI (n, only ROC4Sens)[1)]
  - RD53A → O(80) SCMs available, highest priority
  - ROC4Sens → available earlier, first measurements of small-pitch pixel sensors
- Perform Test Beam measurements at different facilities: SPS(2018), DESY, FNAL

Performance comparison of design variants based on:

- Hit efficiency and spatial resolution (versus incident angle)
- Bias voltage scans
- Threshold scans for inter-pixel coupling (cross-talk)
- Power dissipation (V_{bias} * I_{leak}) per unit area (at -20°C)

Based on measured sensor+ROC performance, choose:

- Layer 1: planar vs 3D
- Sensor thickness (active and total)
- Cell size: 50x50 vs 25x100 μm^2
- Pixel cell design (bias scheme, pixel isolation, ...)

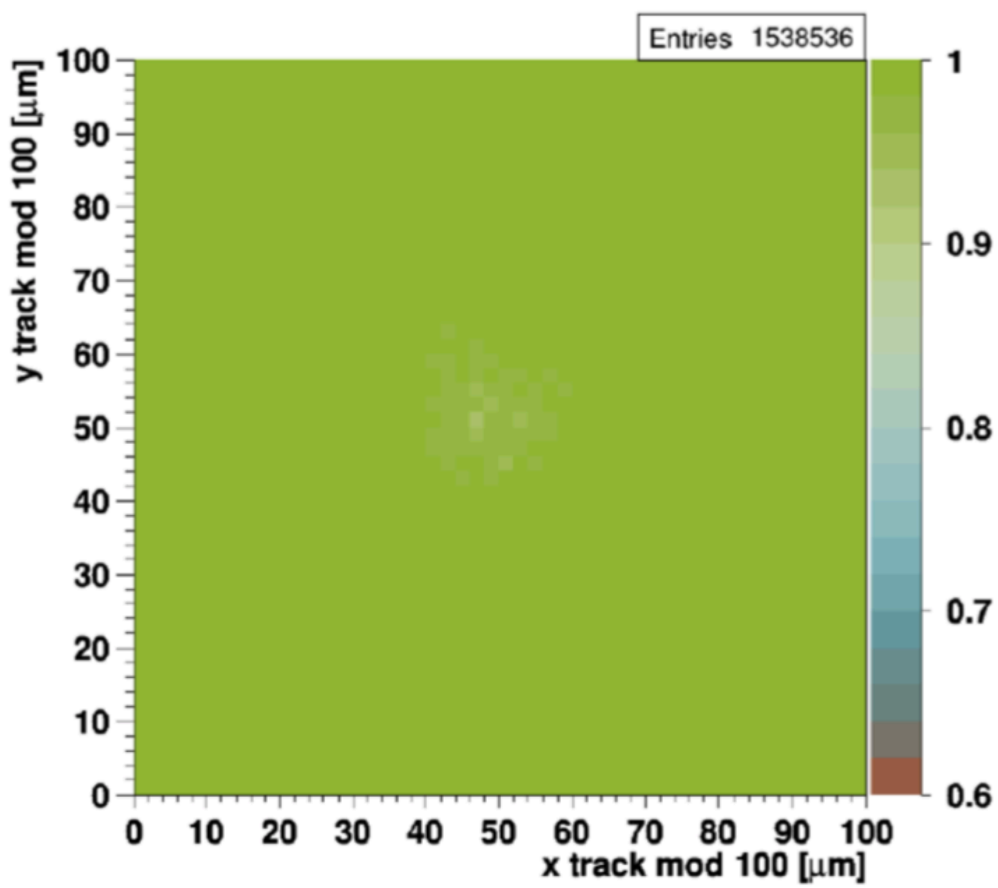


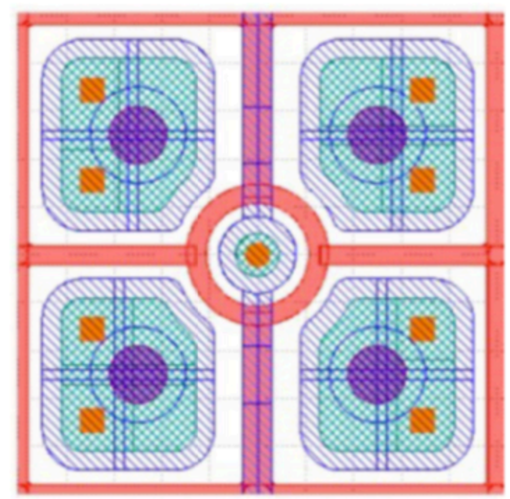
1) This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654168
AIDA 2020

BIAS DOT

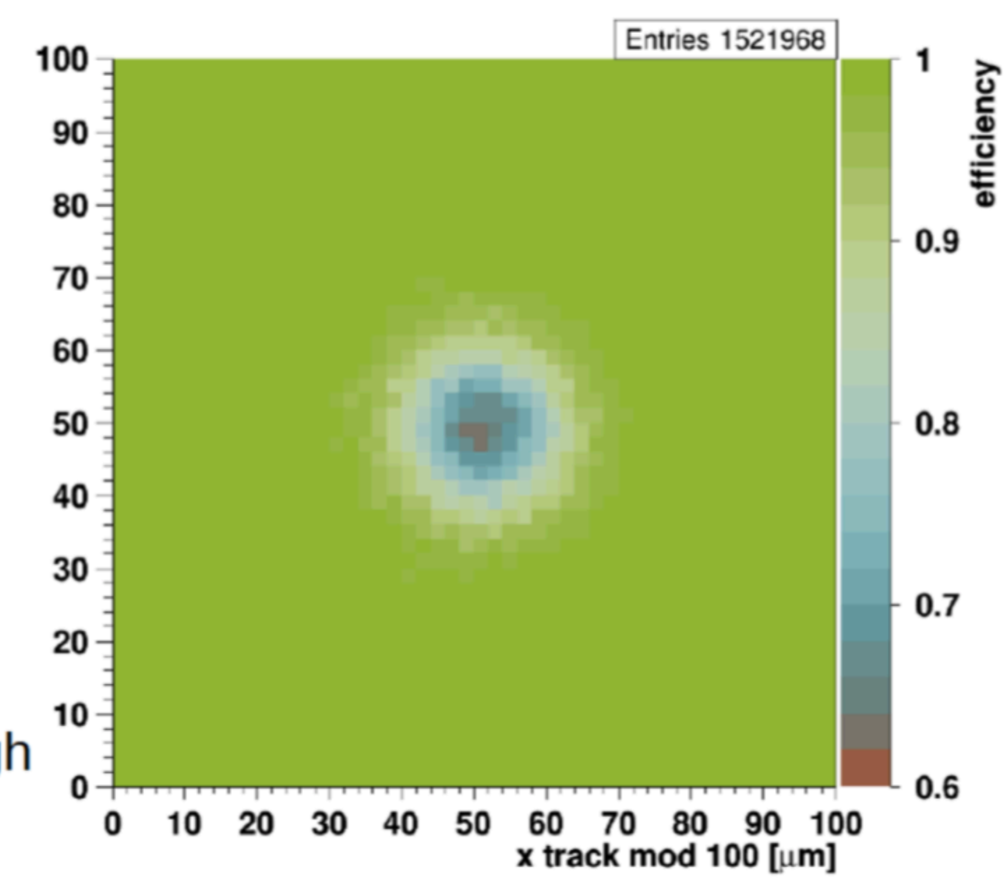
Efficiency maps for bias dot design

- RD53A HPK single chip module
- Beam at vertical incidence (as in Forward pixel, TFPX)





HPK 150X50X50 µm³
Common Punch-through



Biad Grid Floating 99.8%

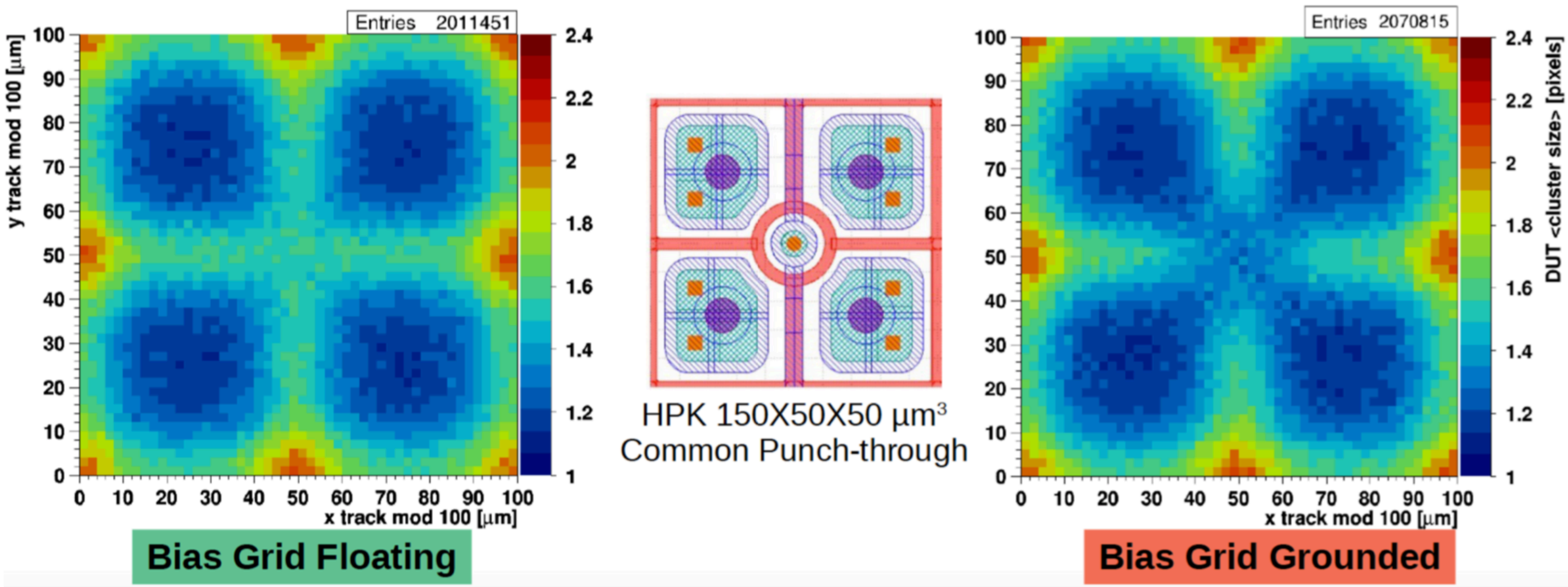
Bias Grid Grounded 98.4%

Higher efficiency with bias dot floating

BIAS DOT

Cluster size maps for bias dot design

- RD53A HPK single chip module
- Beam at vertical incidence (as in Forward pixel, TFPX)

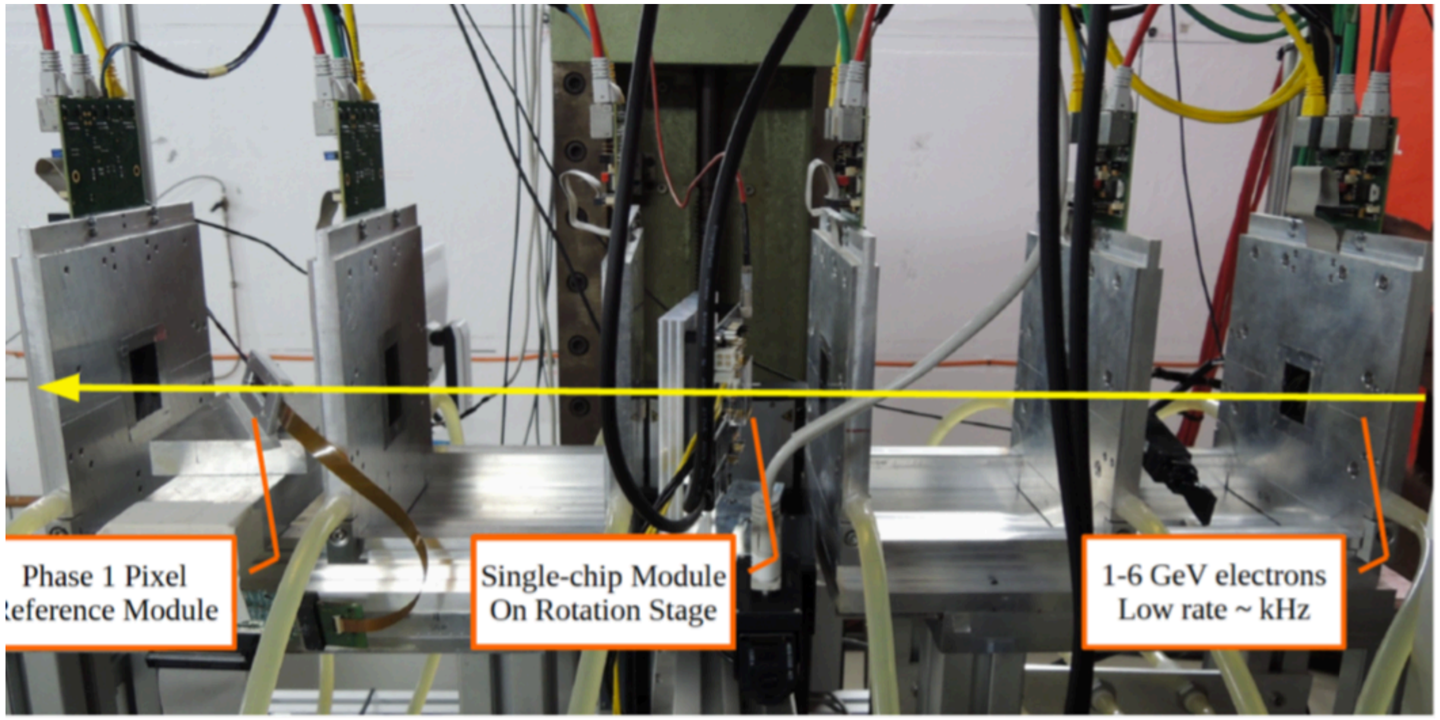


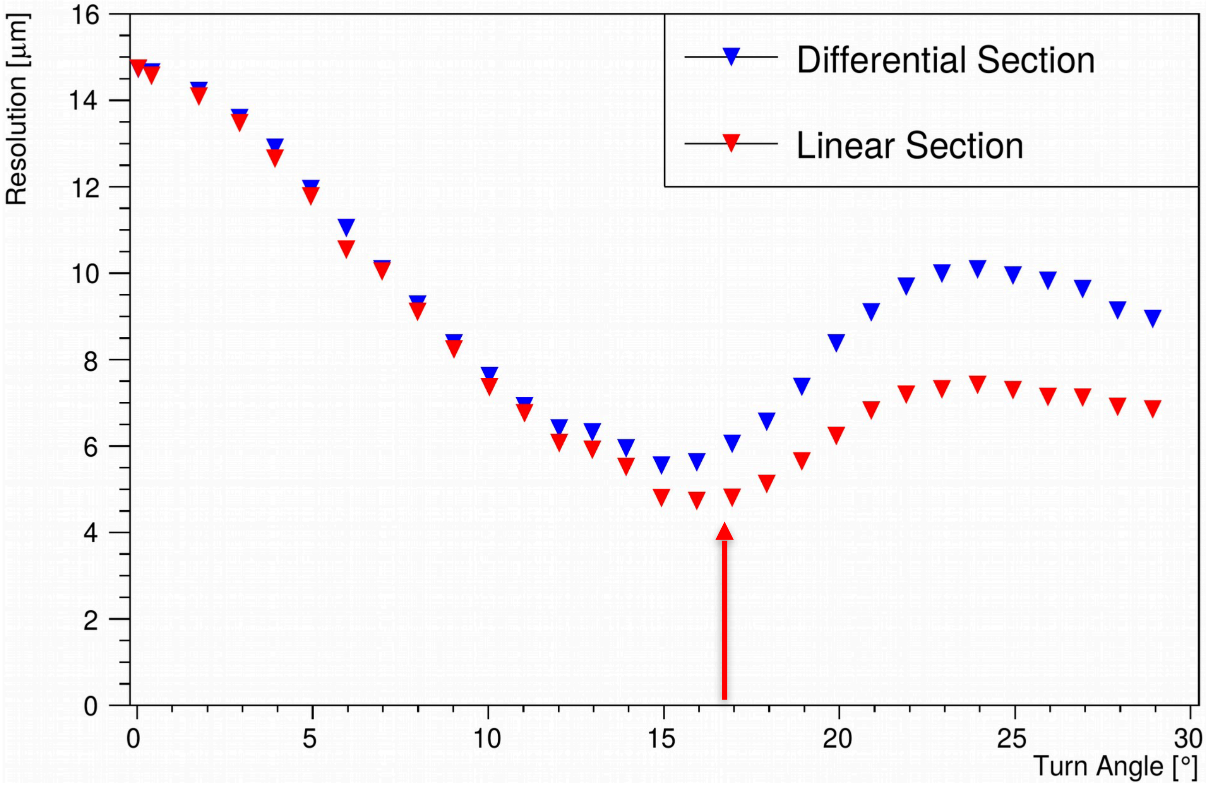
Higher (better) charge sharing between pixels with bias dot floating

SPATIAL RESOLUTION

Excellent spatial resolution confirmed before irradiation

- 50x50 µm² RD53A HPK single chip module
- σ_{hit} = 4.6 µm (unfolded)

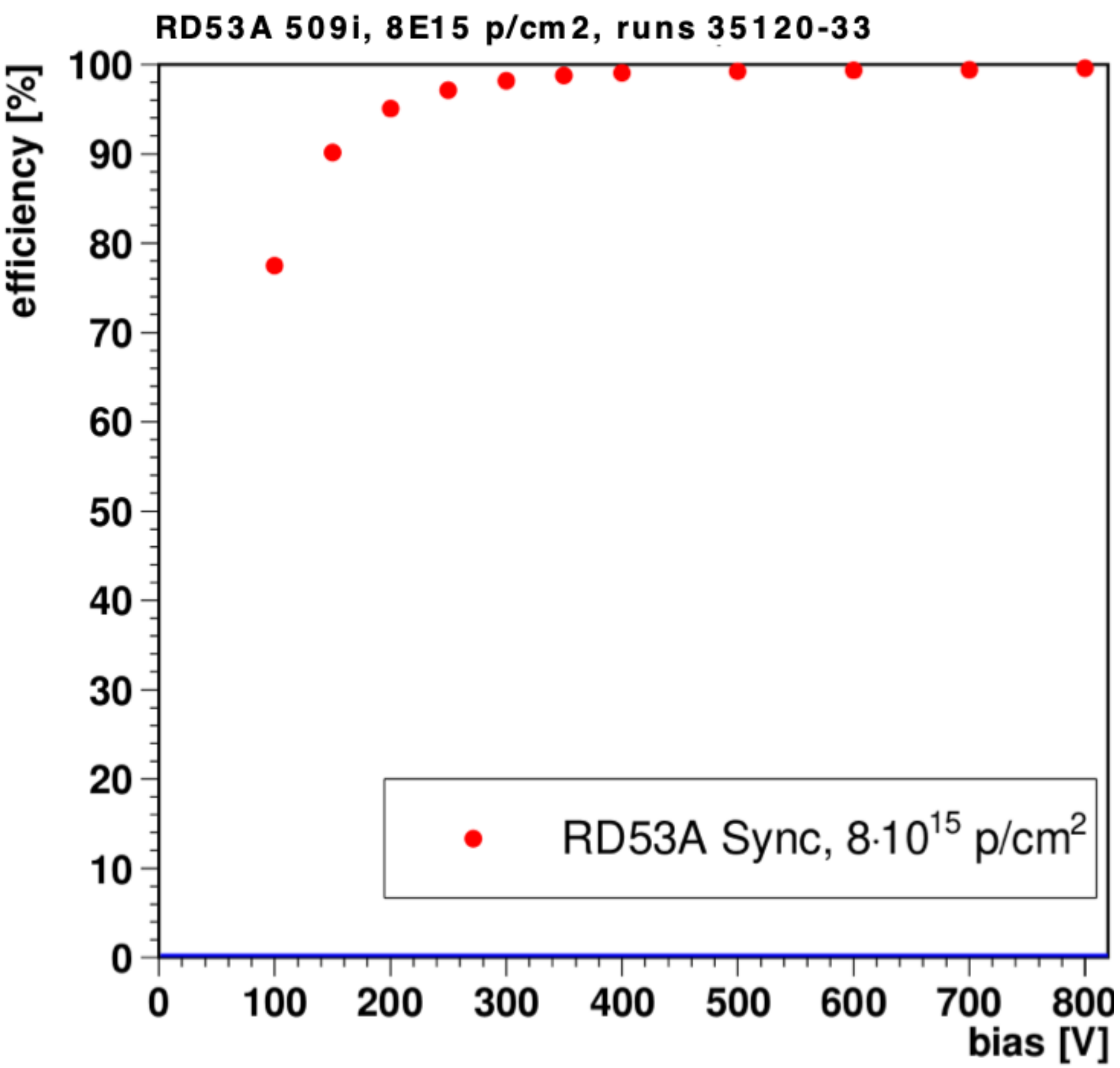




- Optimal turn angle (p: pixel size, d: thickness
  - $\alpha = \arctan(p/d) = 16.7°$
- Calibration of analog front ends ongoing

IRRADIATED RD53A

Efficiency



- **RD53A SCM**: 150 µm thick "FTH"
- **25x100 µm² pixel cell, no bias scheme**
- Fluence **$5x10^{15}$ n_{eq}/cm^2**
- **Linear FE**, threshold trimmed to 1.3 ke
- 101 masked pixels
- vertical incidence

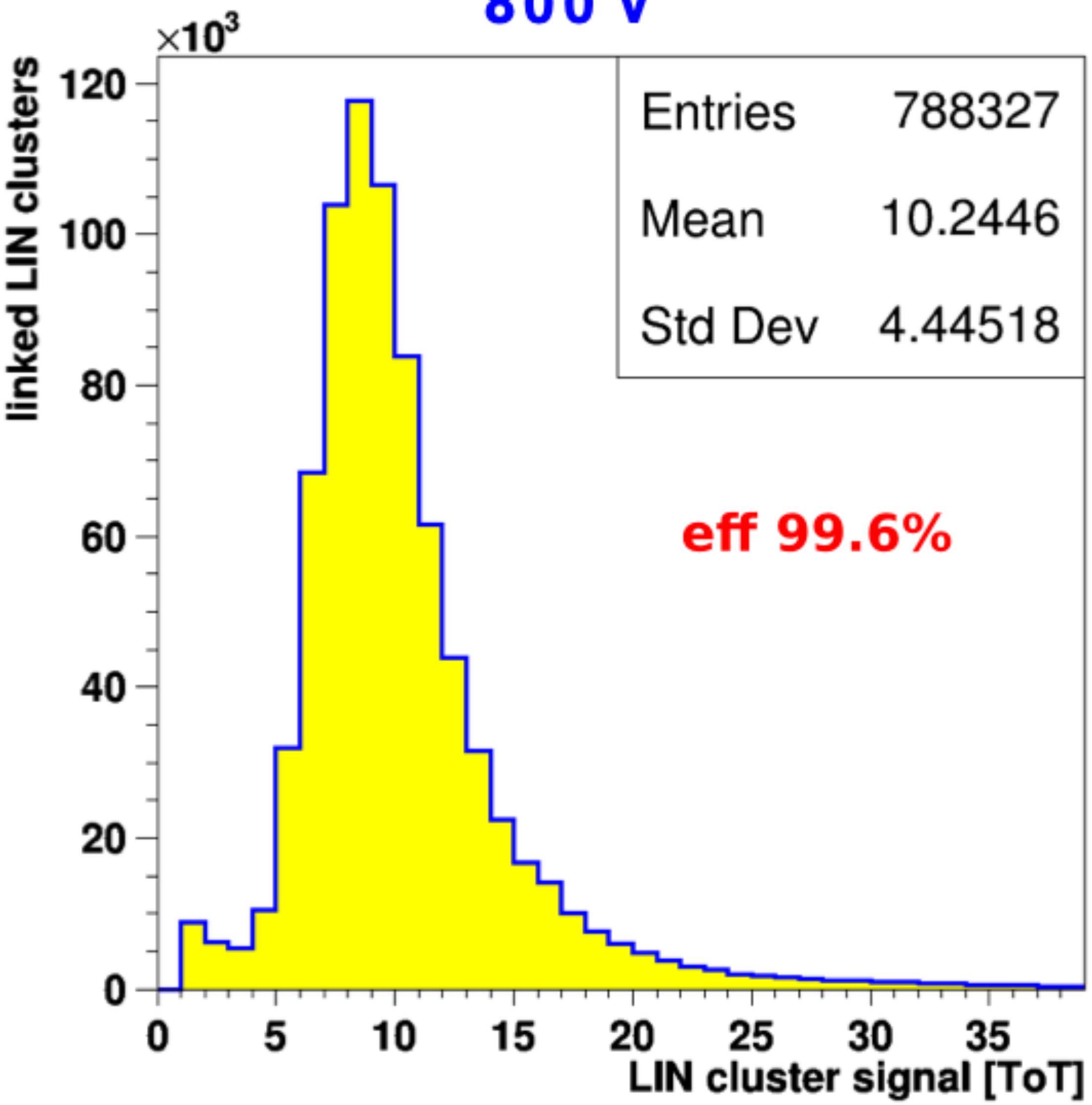
- 400 V needed for 99%, 250 V for 97%

- Caveat: Irradiation non-uniform and dosimetry not well-known

IRRADIATED RD53A

ToT

800 V



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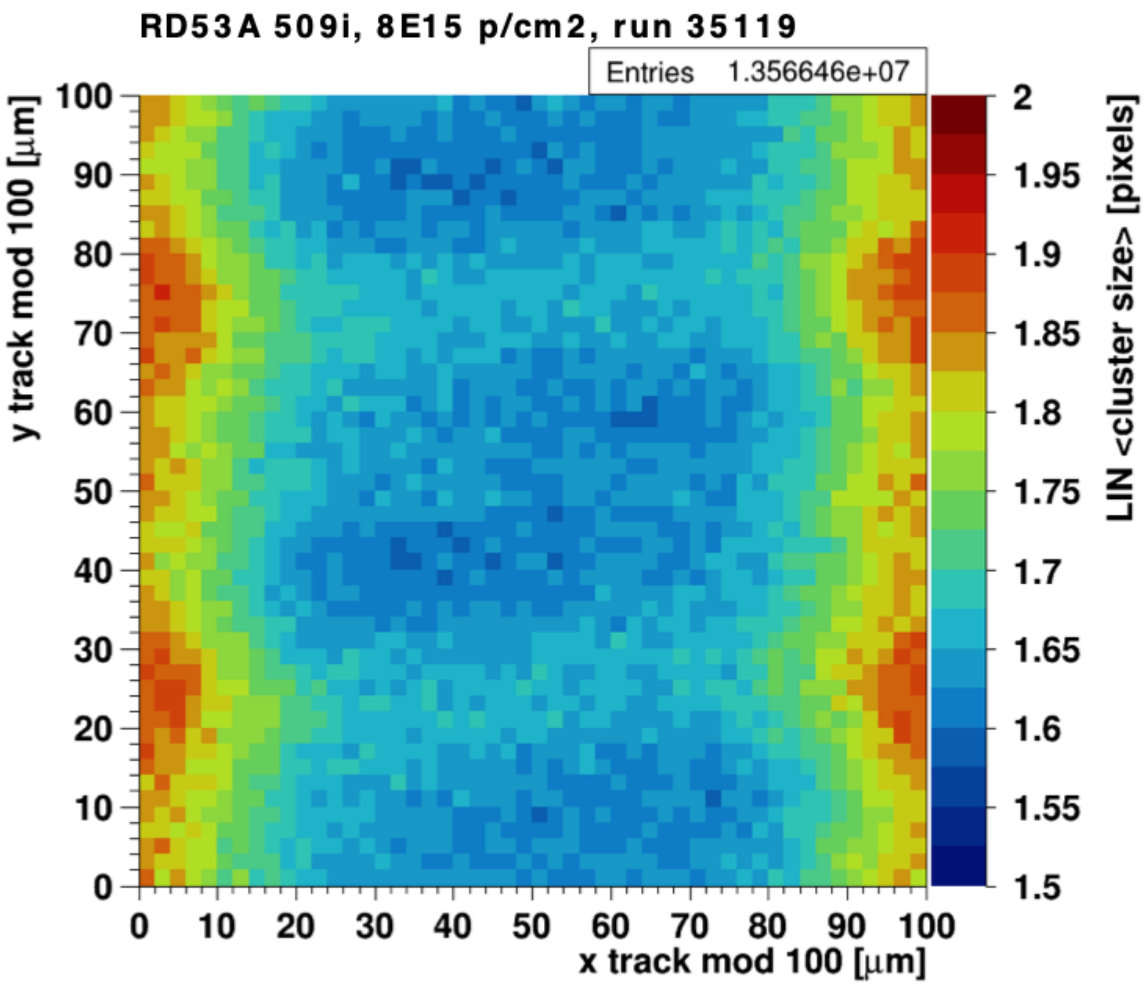
IRRADIATED RD53A

Cluster size



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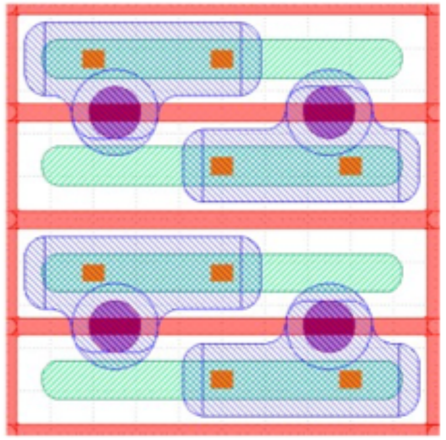
- **25x100 µm² pixel cell, no bias scheme**
- Fluence **$5x10^{15}$ n_{eq}/cm^2**
- **Linear FE**, threshold trimmed to 1.3 ke
- 101 masked pixels
- vertical incidence

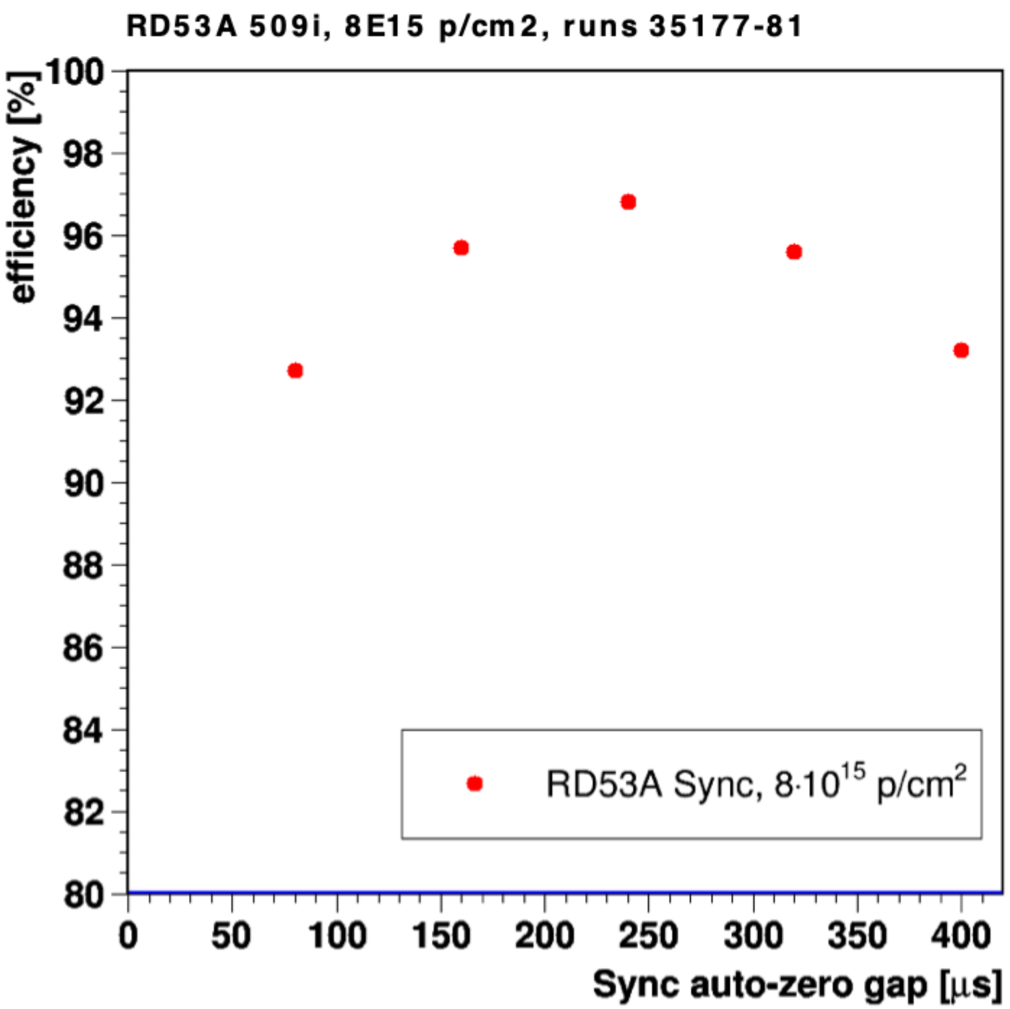
- Metal pattern visible?



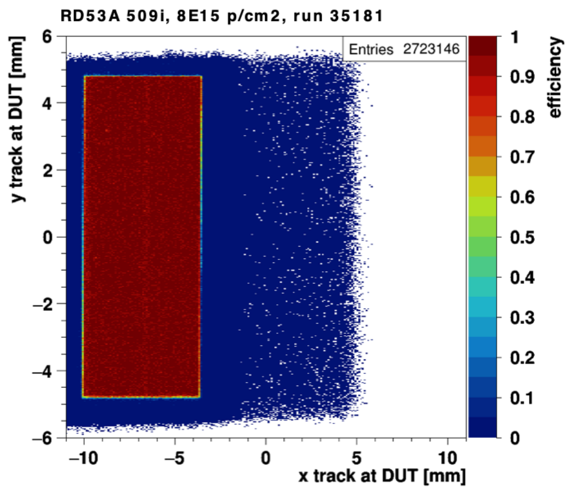
IRRADIATED RD53A

Sync FE

DESY TEST BEAM.



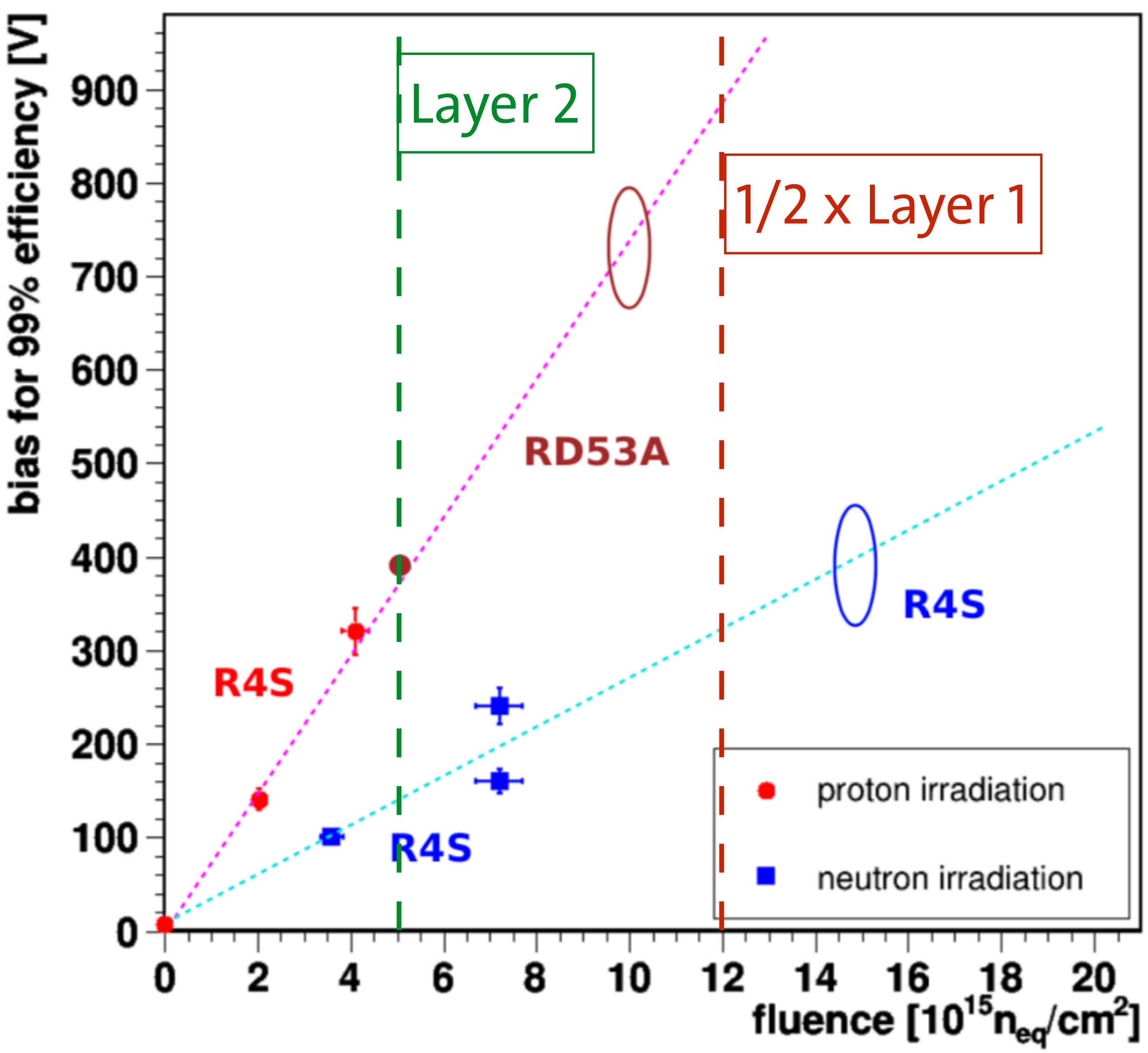
- **Same module as before** (25x100 µm, no bias)
- Fluence $\mathbf{5x10^{15}\ n_{eq}/cm^2}$, 800 V bias
- **Sync FE, threshold trimmed to 1.6 ke**
- Varying auto-zero repetition
  - best compromise: auto-zero pulse 1.6 µs, every 240 µs (4 kHz)
  - **Next test beam: block triggers during auto-zero with NIM hardware chain**
- Efficiency 96.8% in fiducial region (34° turn)



Differential FE too noisy on this module!

NIEL VIOLATION?

V99 vs fluence

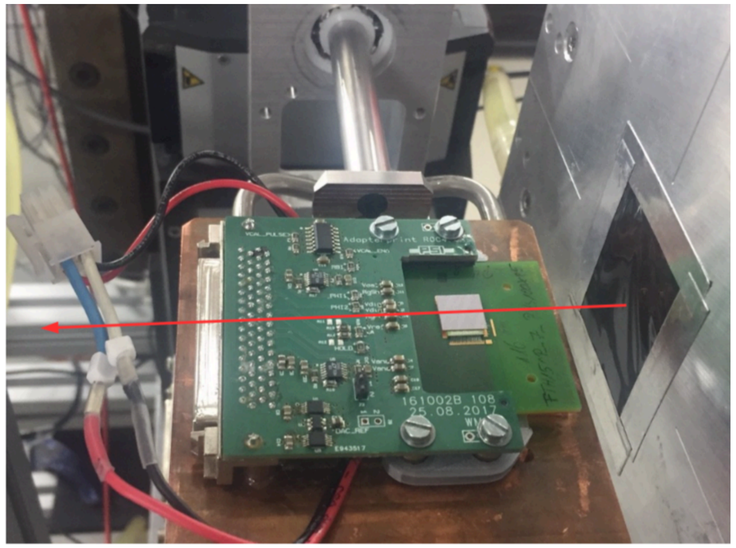


- Bias voltage for 99 % efficiency
  - less than 400 V < $7.2 \times 10^{15}\ n_{eq}/cm^2$
- What is the ultimate reach for planar sensors?
- Next measurements:
  - $1.6 \times 10^{16}\ p/cm^2$
  - $1.6 \times 10^{16}\ n/cm^2$
- Protons vs neutrons
  - NIEL breaking?

EDGE-ON I

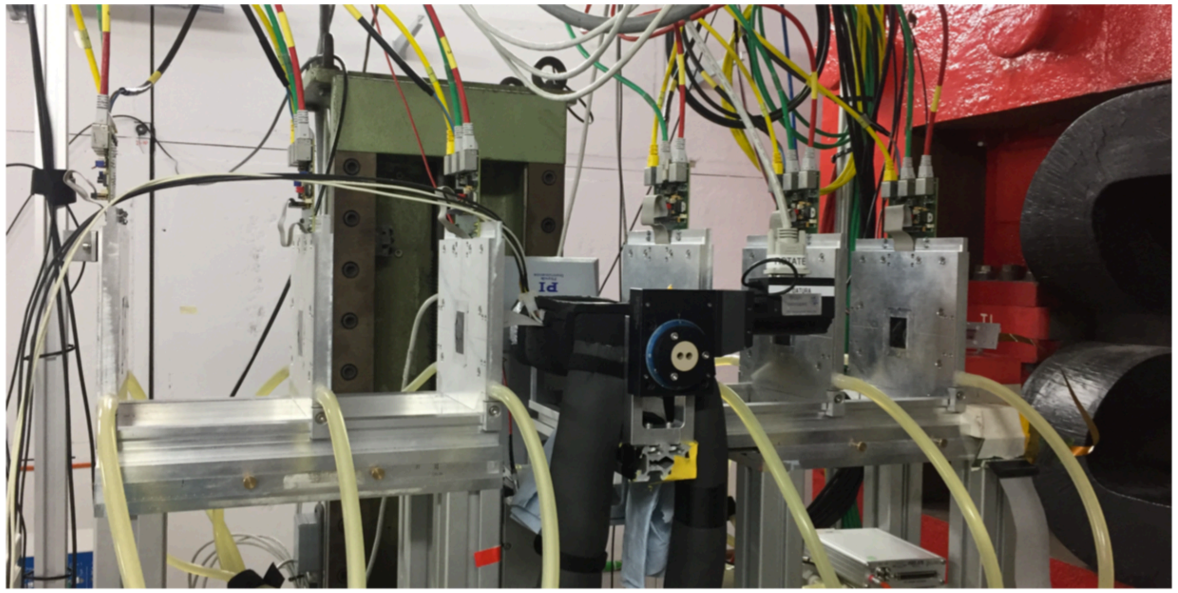
PSI ROC4SENS Chip

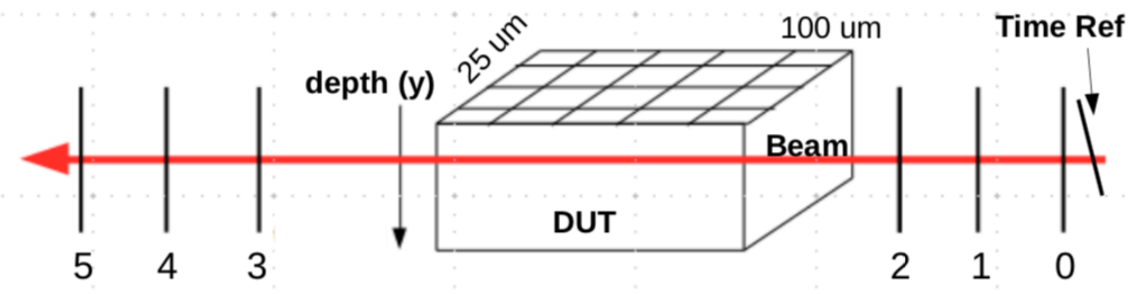
- 24800 pixels (155 columns x 160 rows)
- **No zero suppression**
- **Analog readout**
- Low rate (120 Hz)



Edge on beam test

- At DESY II beam test facility using the EUDET DATURA telescope
- Beam in 100 µm direction parallel to sensor surface
- Track reconstruction using upstream triplet and time reference module



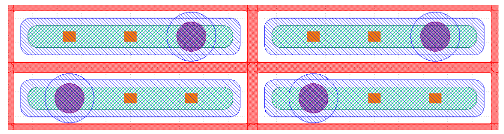


➡Measure charge collection as function of depth + distance to pixel center

➡Allows detailed studies of trapping effects

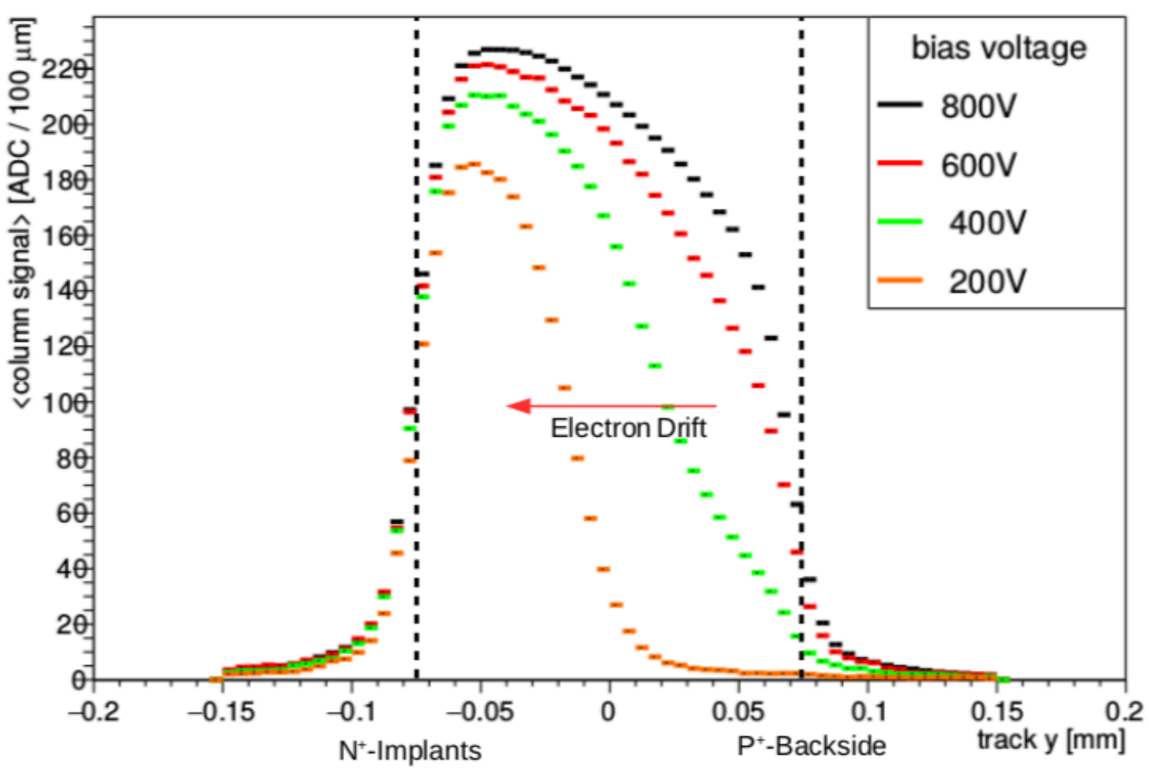
EDGE-ON II

Samples and conditions

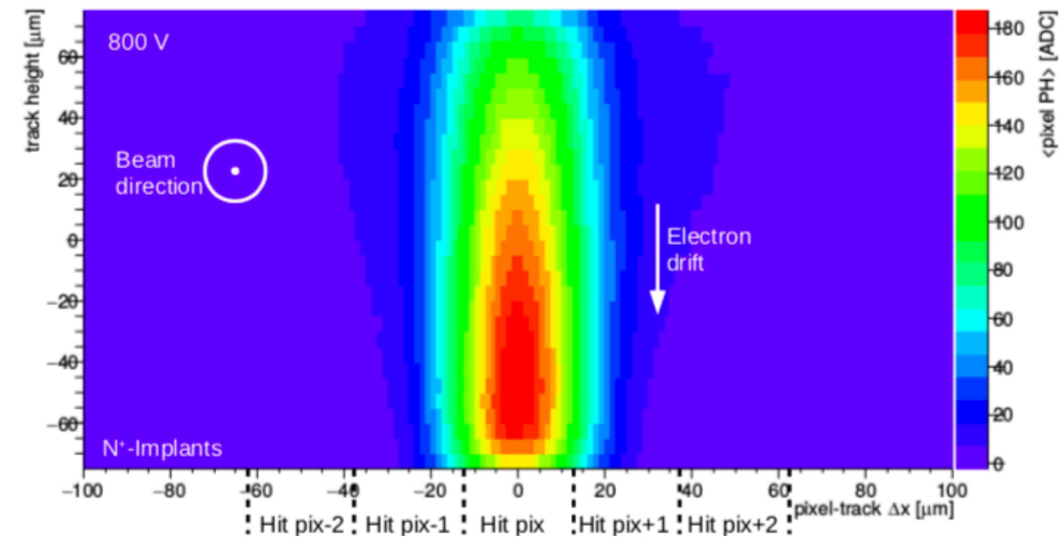


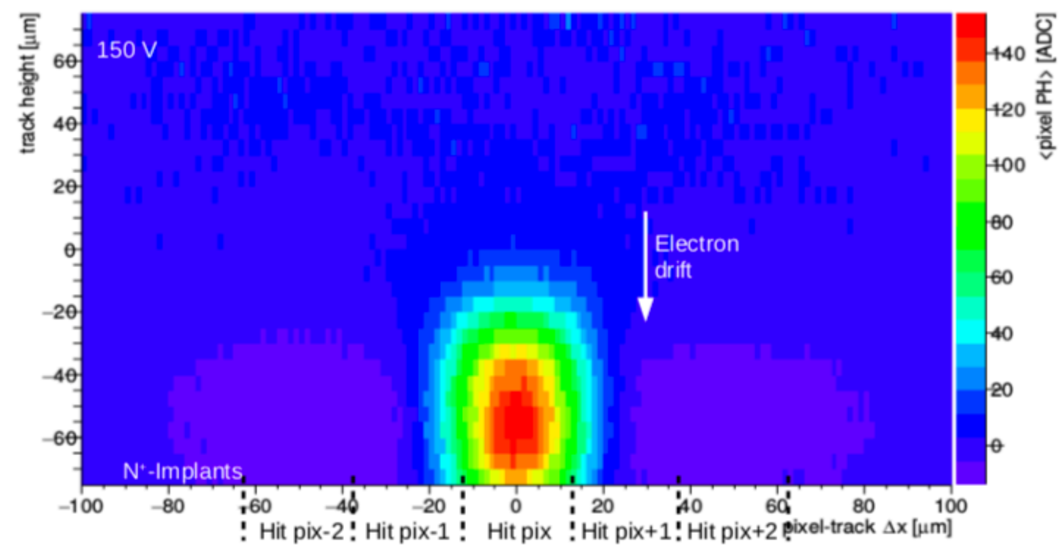
- 100x25 p-stop default
- Irradiated with neutrons to 4×10^{15} cm^{-2}
- T ≈ -24°C
- No additional annealing

Column charge vs depth



Charge collection tomography





- Reconstruct height (y) and x with telescope
- Plot pulse height vs y and pixel-track distance

Complete charge collection and charge sharing information only possible with the ROC4SENS

MULTI-RD53A

- **Quad RD53A** sensor batch for CMS TK common project running at FBK
- Sensor list:
  - **6 doublets (3 quads) No PT 25x100** pixels and no punch through bias. Temporary metal will be used for measurements at FBK premises
  - **14 doublets (7 quads) PT 50x50** pixels with punch through bias
  - **15 singlets with 25x100 or 50x50** pixels
- Wafer material (Icemos)

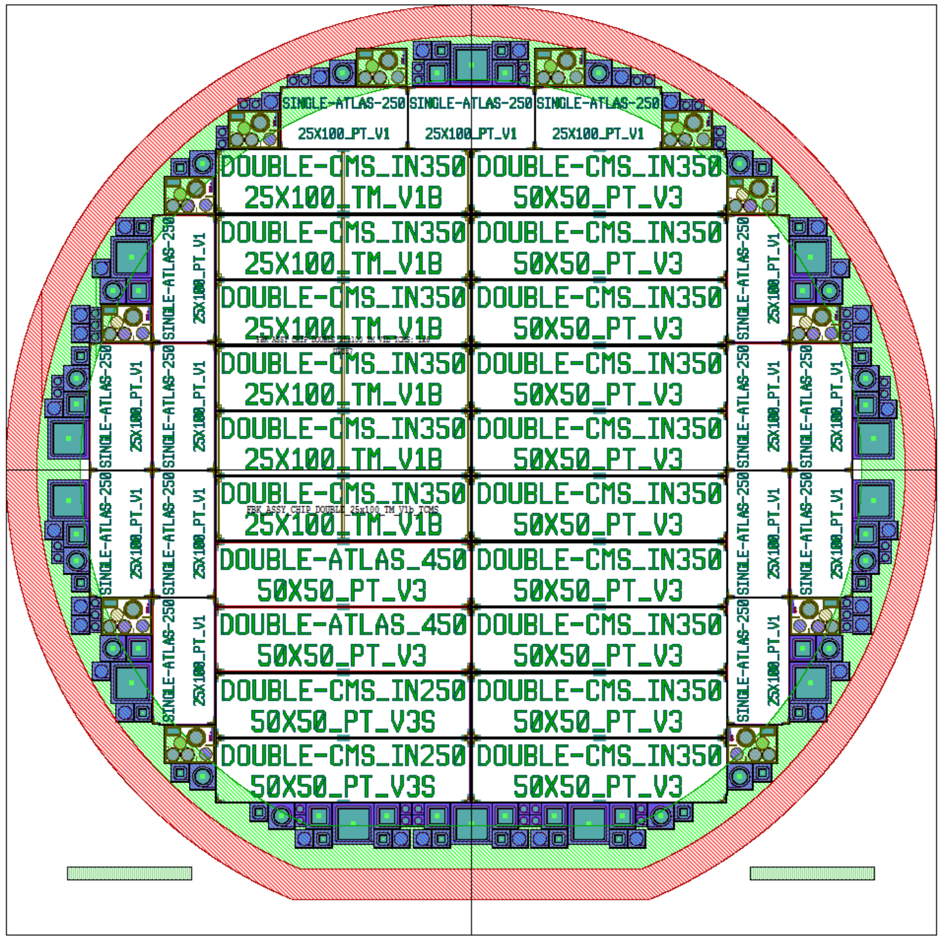
  6" Float Zone Si-Si DBW (Direct Bonded Wafer)

  150 µm thick active device, on 500 µm handle

  P type, FZ Sensor resistivity > 5 kΩ·cm

  Handle wafer: CZ 0.1-1 Ohm cm resistivity
- Three singlets with **slim edge**!

  Distance last pixel implant to dicing line: **230, 180 and 130** µm (real distance will be smaller after dicing)



SUMMARY

- Intense IT planar sensor R&D campaign with HPK, FBK
- Test beam results:
  - **Before irradiation:** Only small differences observed in efficiency between pixel cell designs,
    in particular between **common punch through vs. no bias**
  - Planar sensors **tested to Layer 2 lifetime fluence (5x10^{15} n$_{eq}$/cm^2)**:
    - 400 V bias needed for 99% hit efficiency,
    - 99.6% at 800 V (HPK sensor without bias grid)
- Detailed performance comparison of cell designs after irradiation, and determination of ultimate reach of planar pixels: Ongoing