The INFN-FBK "Phase-2" R&D Program

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On behalf of the INFN-FBK Phase-2 Collaboration

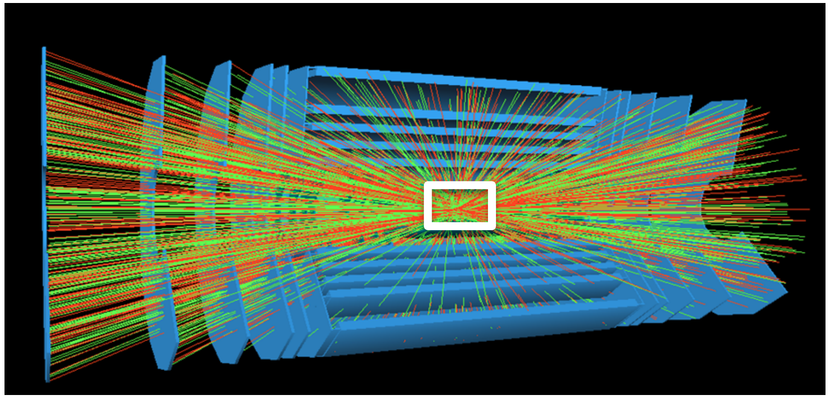
Frontier Detectors for Frontier Physics
13th Pisa Meeting on Advanced Detectors
24–30 May 2015 ● La Biodola, Isola d'Elba (Italy)

Outline

- Introduction
- R&D program
- Status
  - Planar sensors
  - Technology tests for new 3D sensors
  - 3D design and simulations
- Conclusions

Pixel Roadmap LHC → HL-LHC

N. Wermes, 9th TN Workshop (Genova, 2014)



Increased luminosity requires

- higher hit-rate capability
- increased granularity
- higher radiation tolerance
- lighter detectors

Next ROC generation (RD53 65 nm)

50x50 μm^2 and 25x100 μm^2 pixels

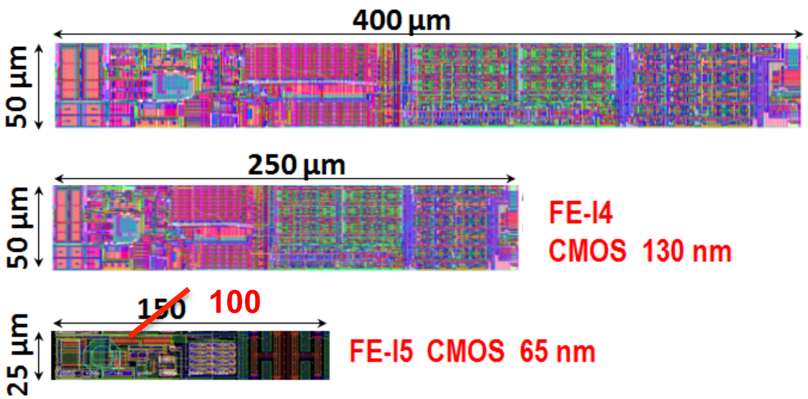
$C_{DET} \leq 100$ fF

$I_{leak} \leq 10$ nA/pixel (no amp. comp.)

Threshold: ~1000 electrons

G. Darbo, CSN5-ACTIVE, 2013

ATLAS roadmap → Pixel Size



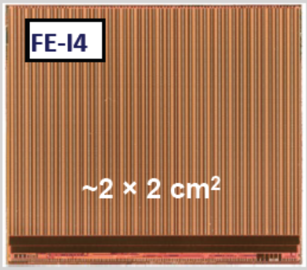
2003 FE-I3 CMOS 250 nm

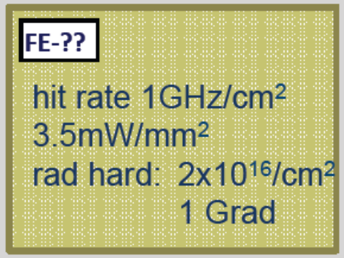
2010 FE-I4 CMOS 130 nm

2017-18 FE-I5 CMOS 65 nm

ATLAS Pixel FE chips

~0.6 × 1.1 cm²





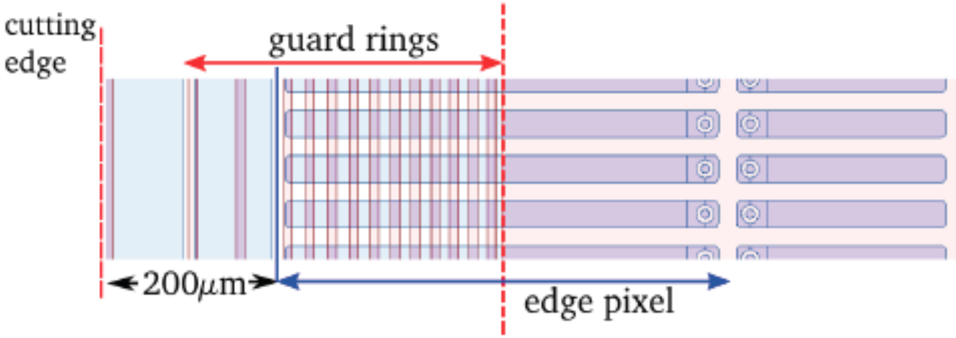
250 nm technology	130 nm technology	65 nm technology
pixel size 400 × 50 μm^2	pixel size 250 × 50 μm^2	pixel size 125 × 25 μm^2
3.5 M. transistors	70 M transistors	~ 500 M transistors

HL-LHC ATLAS and CMS Pixel TDR: 2017

State of the art in Si hybrid pixels for HEP

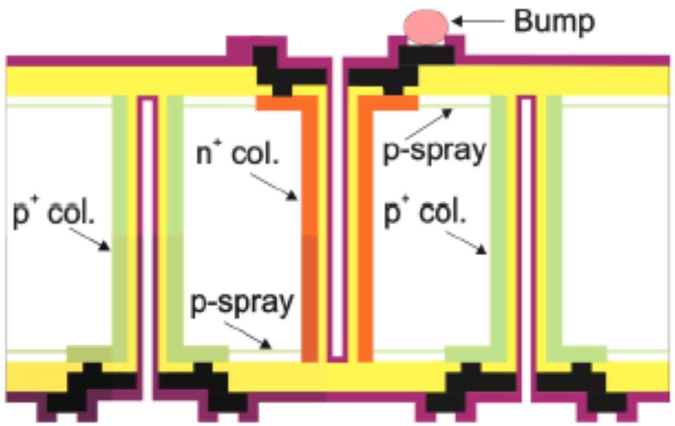
ATLAS IBL pixels

- Planar n-on-n (200 μm thick)



S. Altenheiner et. al. JINST 7 (2012) C02051

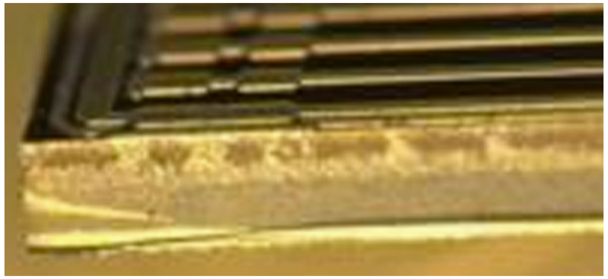
- Double-sided 3D (230 μm thick)



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

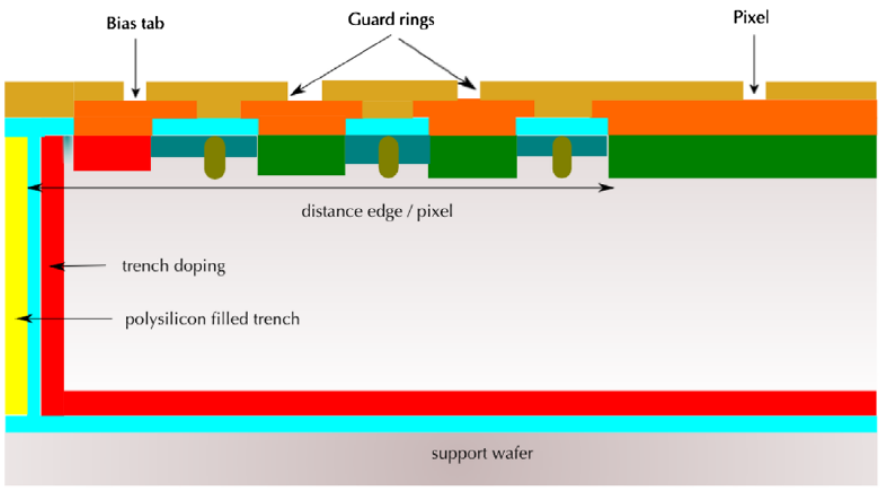
Other emerging technologies

- Planar n-on-p
- Slim and active edges



Scribe
Cleave
Passivate

V. Fadeyev et al., NIMA 731 (2013) 260



M. Bomben et al., NIMA 730 (2013) 215

The INFN-FBK "Phase-2" R&D program

- Initially proposed in 2013 as INFN CSN5 Call project "ACTIVE" (ATLAS and CMS Towards InnovatiVe pixEls), but not approved
- Funded from 2014 by INFN CSN1 "RD_FASE2" and INFN-FBK-PAT "MEMS3" agreement

12 INFN GROUPS INVOLVED, ~20 FTE

ATLAS (BO, CS, GE, MI, TN, UD), **CMS** (BA, FI, MIB, PG, PI, TO)

GOAL: development of new thin 3D and Planar Active Edge (PAE) pixel sensors on 6" p-type wafers at FBK:

- Technology and design to be optimized and qualified for extreme radiation hardness (2×10^{16} n_{eq} cm^{-2})
- Pixel layouts compatible with present (for testing) and future (RD53 65nm) FE chips of ATLAS and CMS

Strong sinergy with WP7 of AIDA2020

Main R&D issues

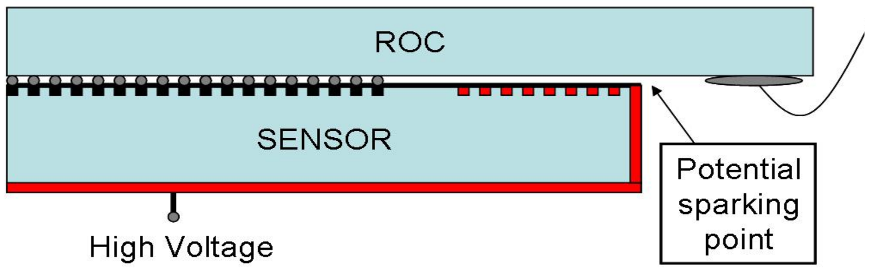
SENSORS (with FBK)

- Processing thin sensors (~100 μm active layer)
- High densities of small pixels
- Radiation hardness (up to 2×10^{16} n_{eq} cm^{-2})
- Active or very slim edges (~100 μm)

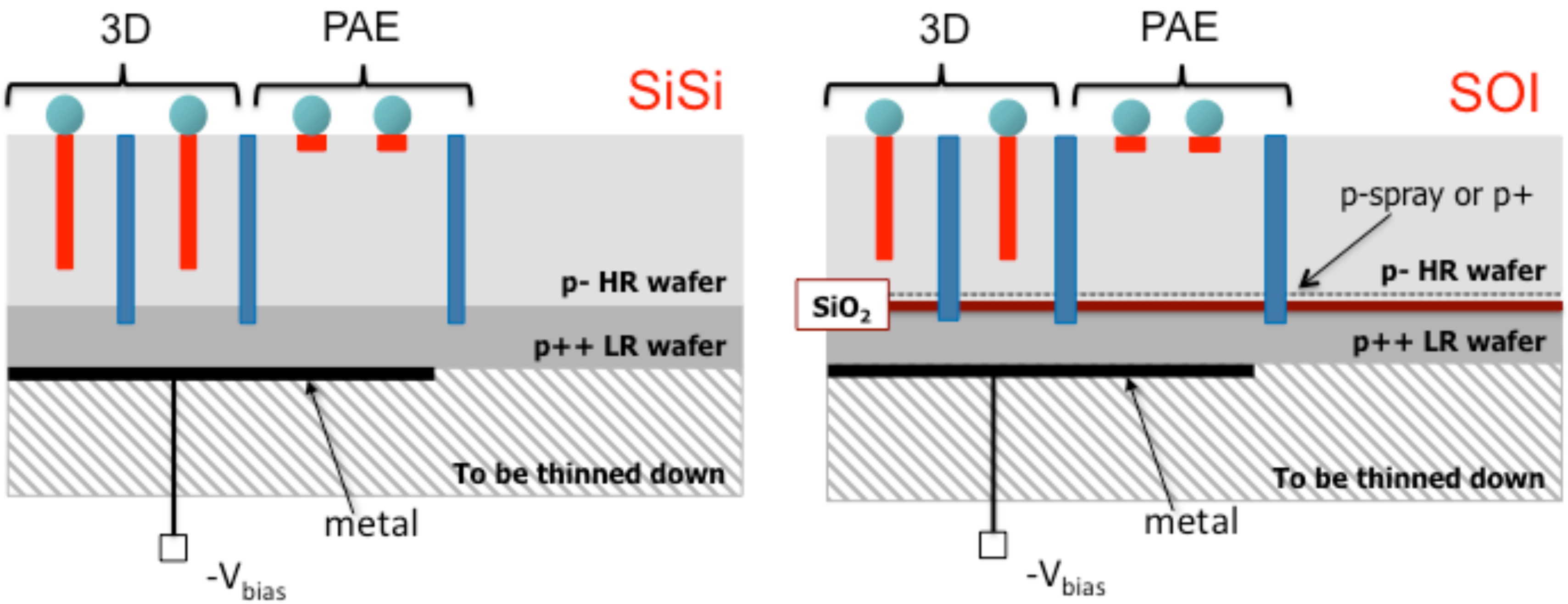
Focus of the talk

BUMP BONDING (with Selex and IZM)

- High densities of bumps (~130000) on large areas (~4cm^2)
- Back-end processing:
  - ROC and sensor thinning
  - Metallization
  - Surface insulation for spark protection (BCB, 5300 V/μm)



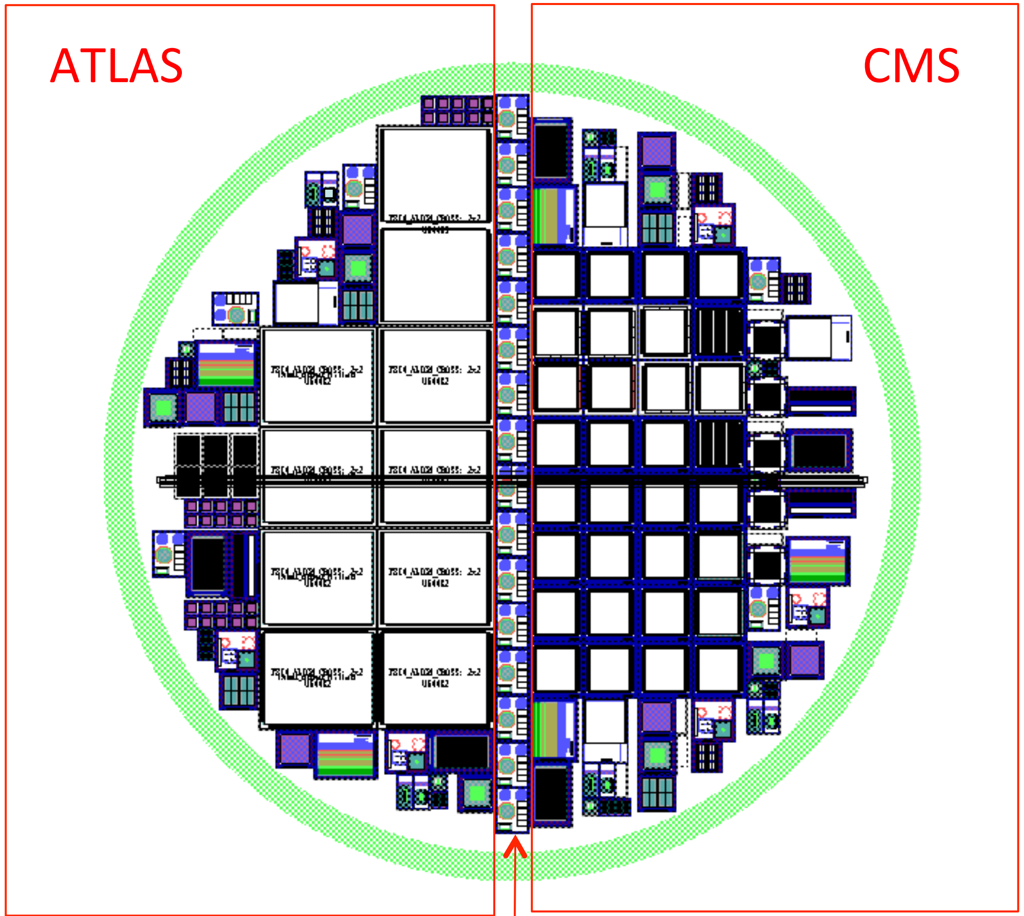
New single-side approach to 3D/PAE



- Thin sensors on support wafer: SiSi or SOI → Substrate qualification
- Ohmic columns/trenches depth > active layer depth (for bias)
- Junction columns depth < active layer depth (for high V_{bd})
- Reduction of hole diameters to ~5 um
- Holes (at least partially) filled with poly-Si

Process Tests

Planar test batch



Test structures for SiSi DWB substrate qualification

Wafers

6" Si-Si silicon wafers (ICEMOS), 100±2μm and 130±2μm sensor layer thickness with ρ>3000 Ωcm (+500±10μm support wafer)

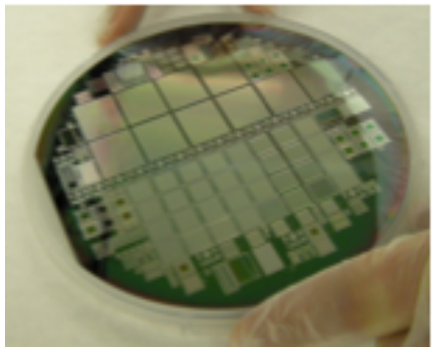
Process

- n-on-p planar process
- three different p-spray doses

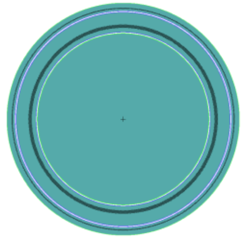
Layout

- 10 ATLAS pixels (FEI4)
- 32 CMS pixels (PSI46)
- Many test structures

Batch completed at FBK in Dec. 2014

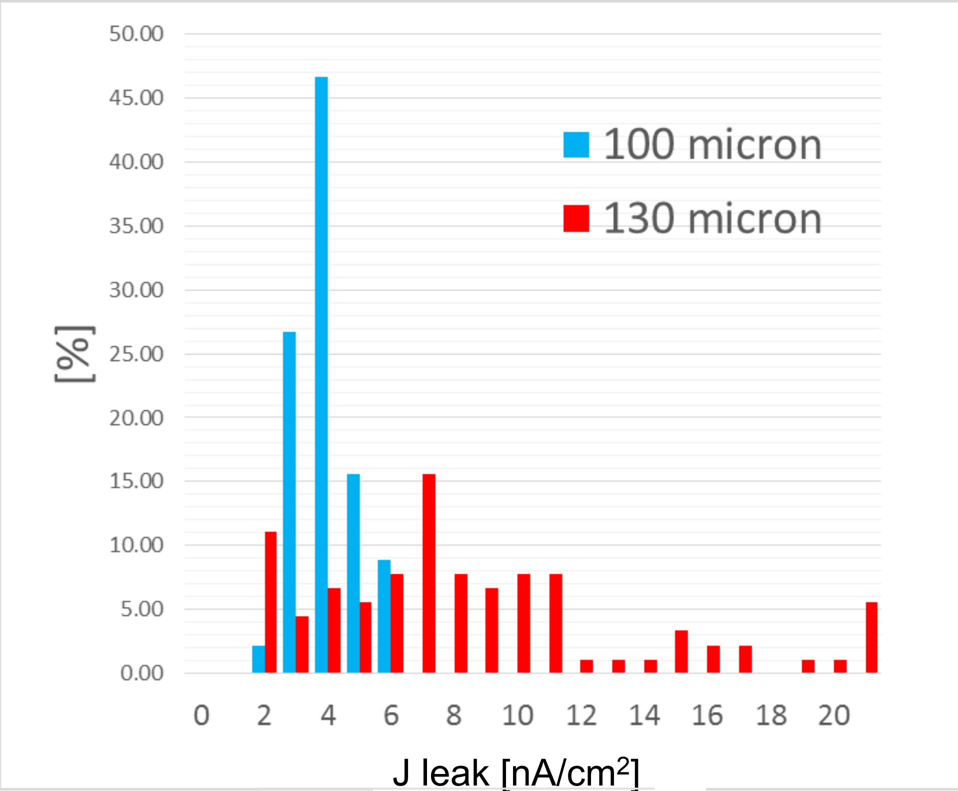


Test diode: I-V measurements



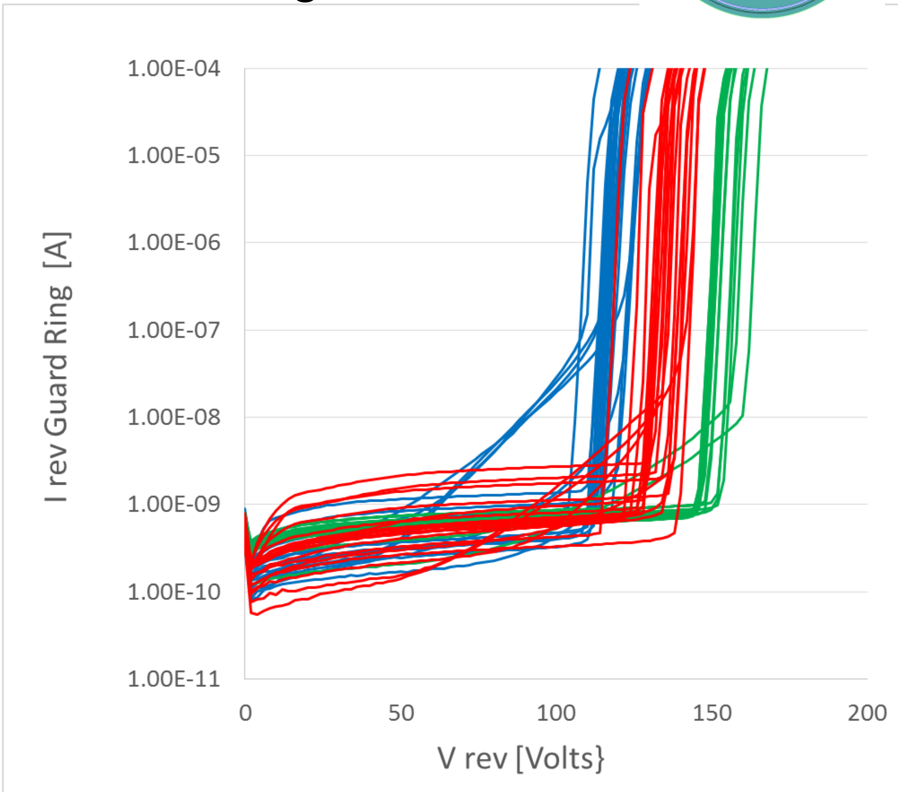
Measured at FBK up to 200 V

Circular diode, 4 mm^2, two Guard Rings



J_{leak} distribution on 135 diodes

→Different material quality ?



Guard Ring reverse currents on 3 wafers with 3 p-spray doses: Low Medium High (correct V_{bd} trend)

Test diode: C-V measurements

Measured at FBK

Depletion voltages:

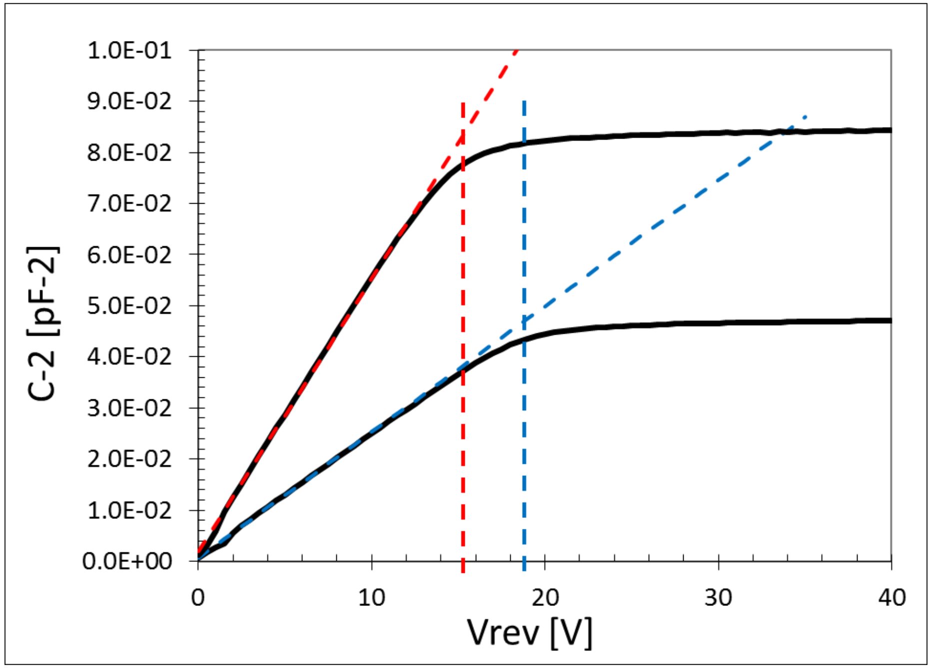
- V_{depl} ~ 16V for 100 μm thick.
- V_{depl} ~ 20V for 130 μm thick.

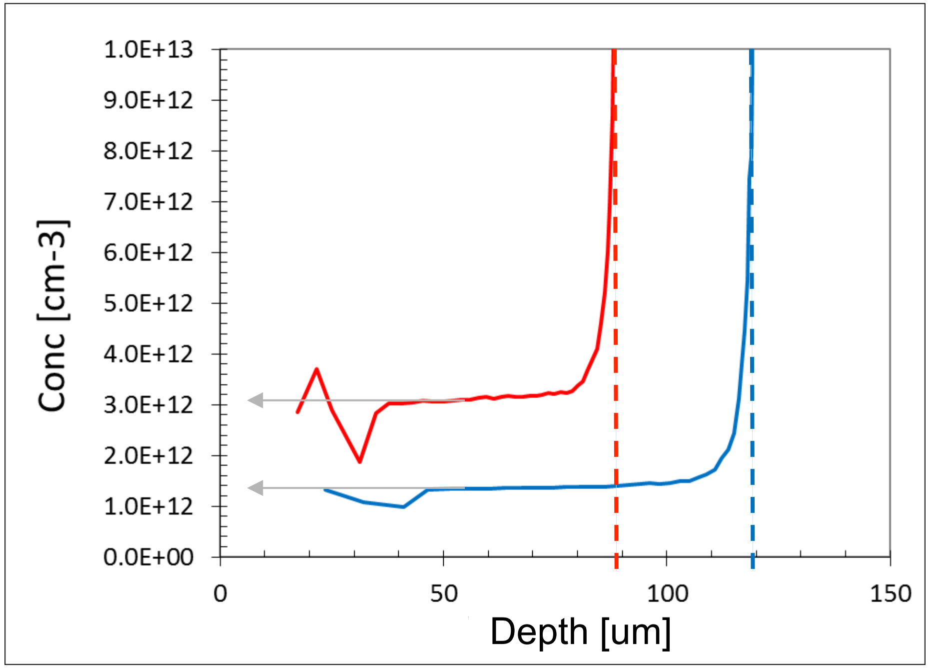
do not scale with square of thickness

→ Different resistivities …

Concentration profiles

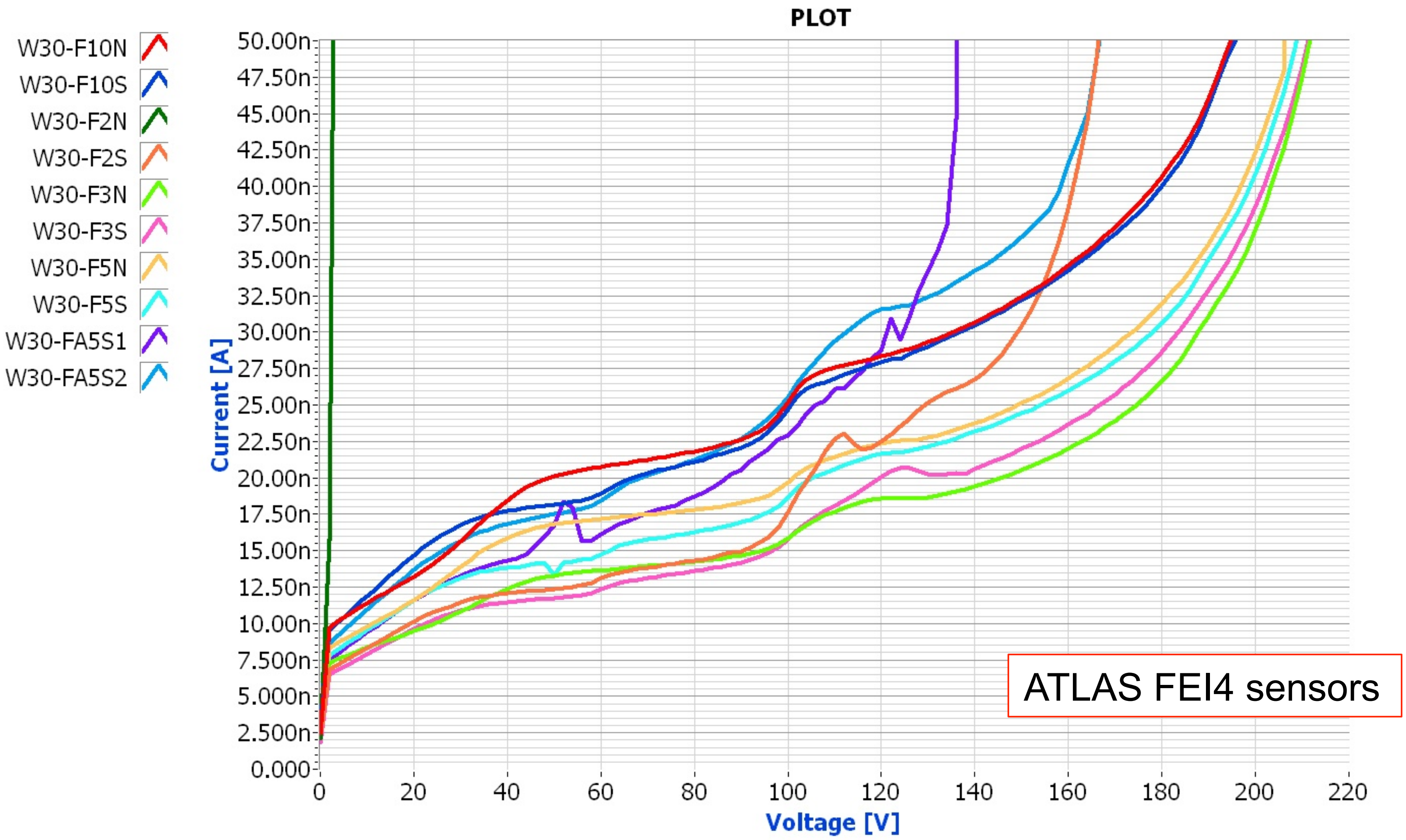
- Doping 1 – 3 x 10^{12} cm^{-3}
- Thicknesses about 10 μm lower than the nominal values, compatible with Boron diffusion from support wafer and measurement limit (L_{debye})





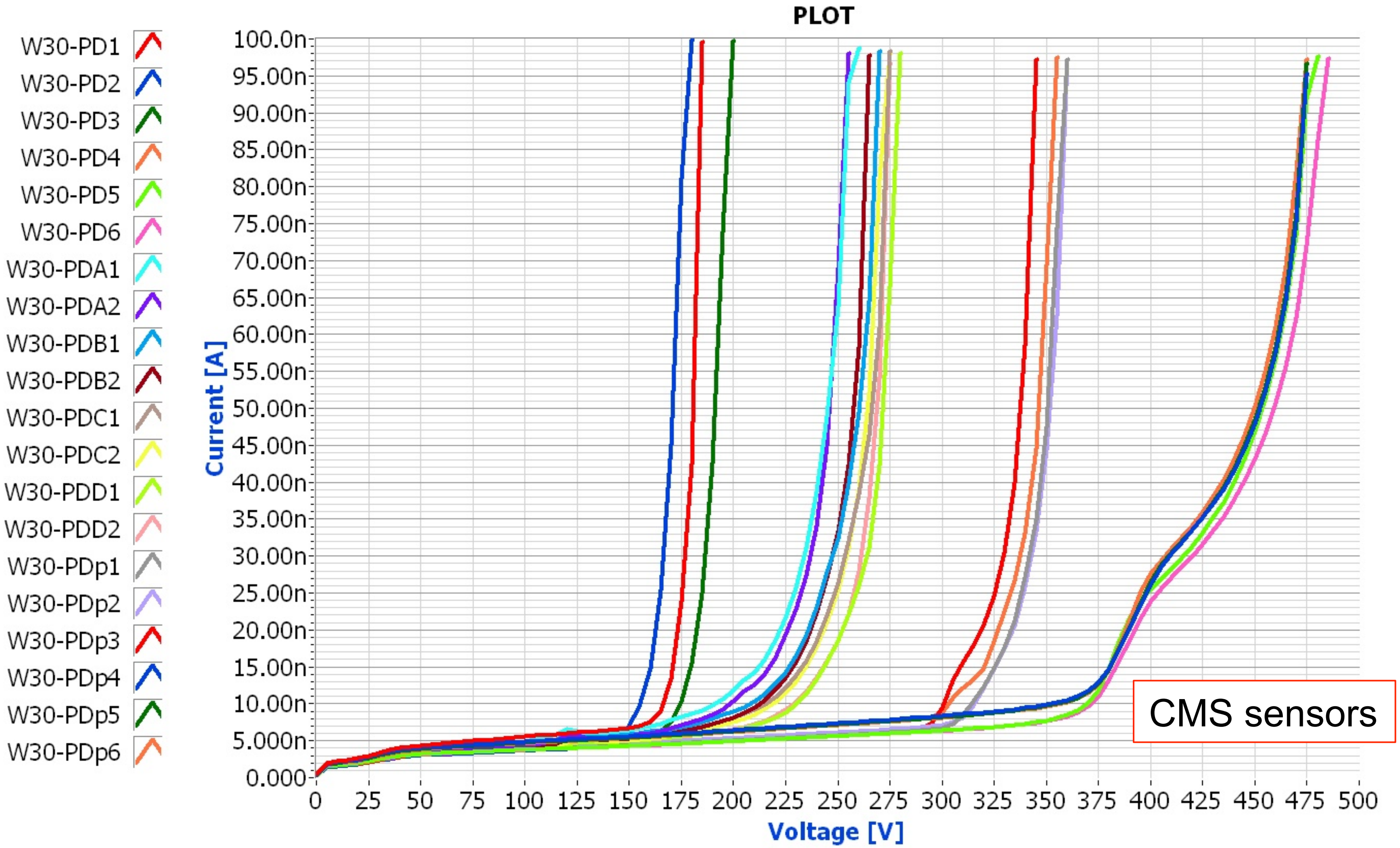
Pixel sensors I-V measurements (1)

Measured at INFN Firenze up to high voltage

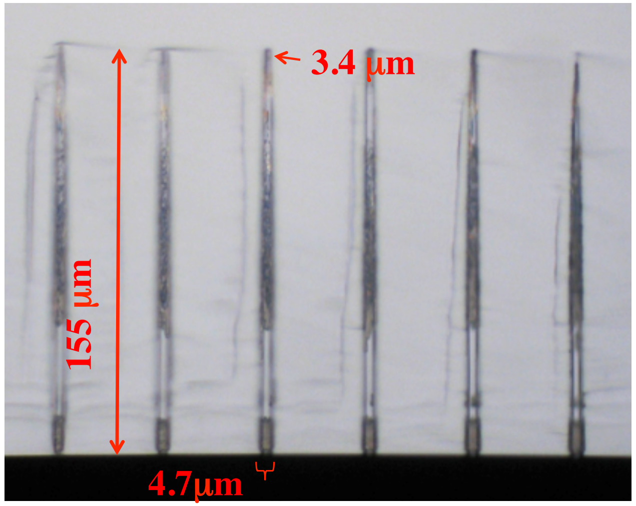


Pixel sensors I-V measurements (2)

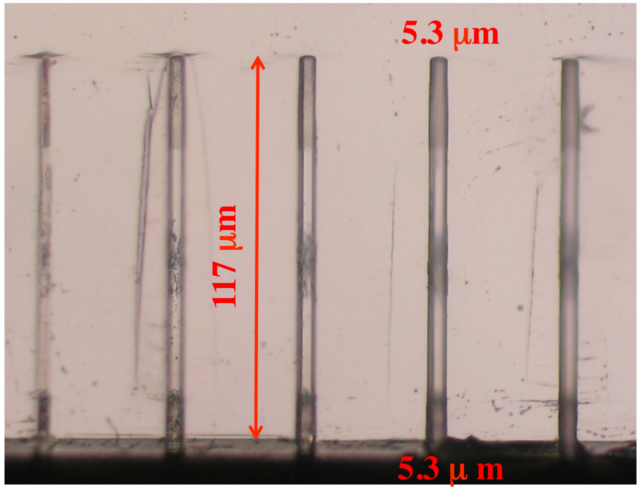
Measured at INFN Firenze up to high voltage



Etching narrow columns by DRIE

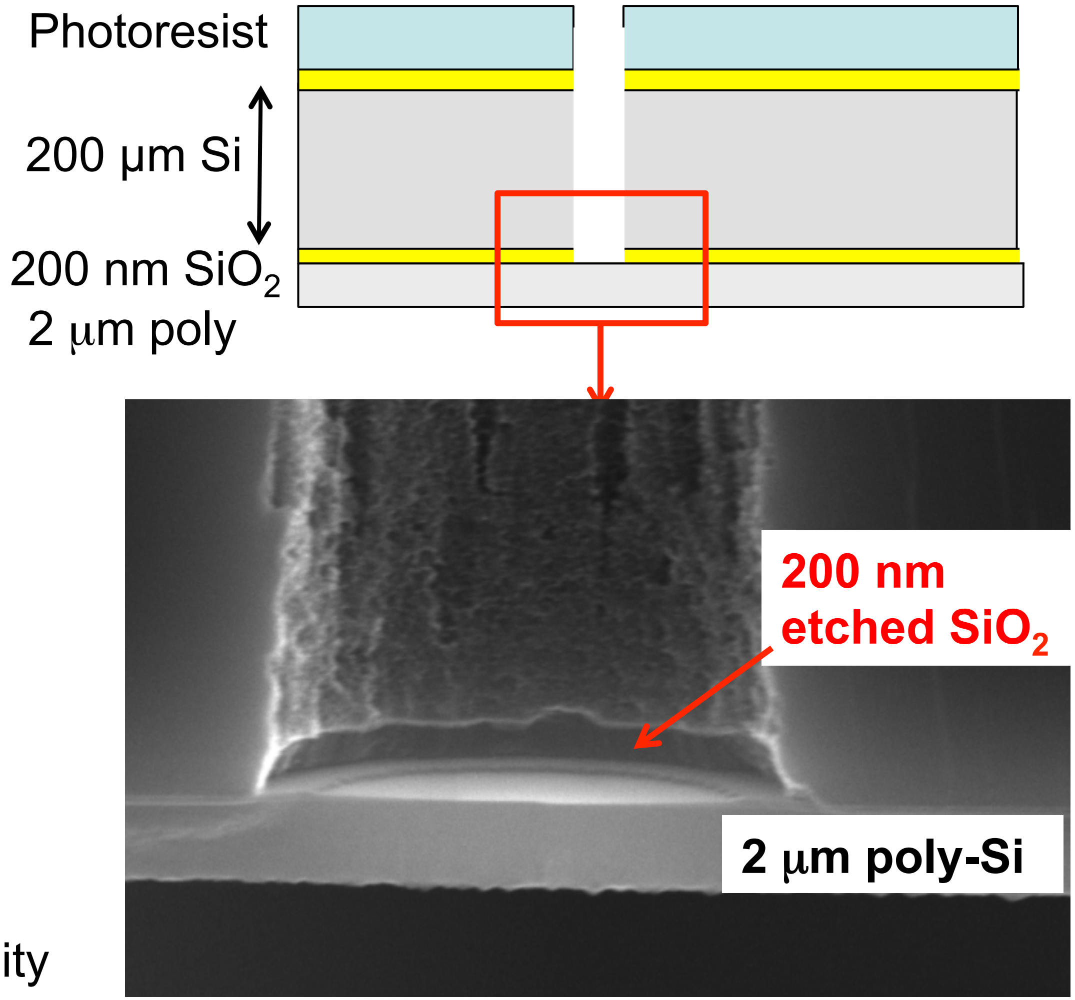


Ohmic columns optimized for depth



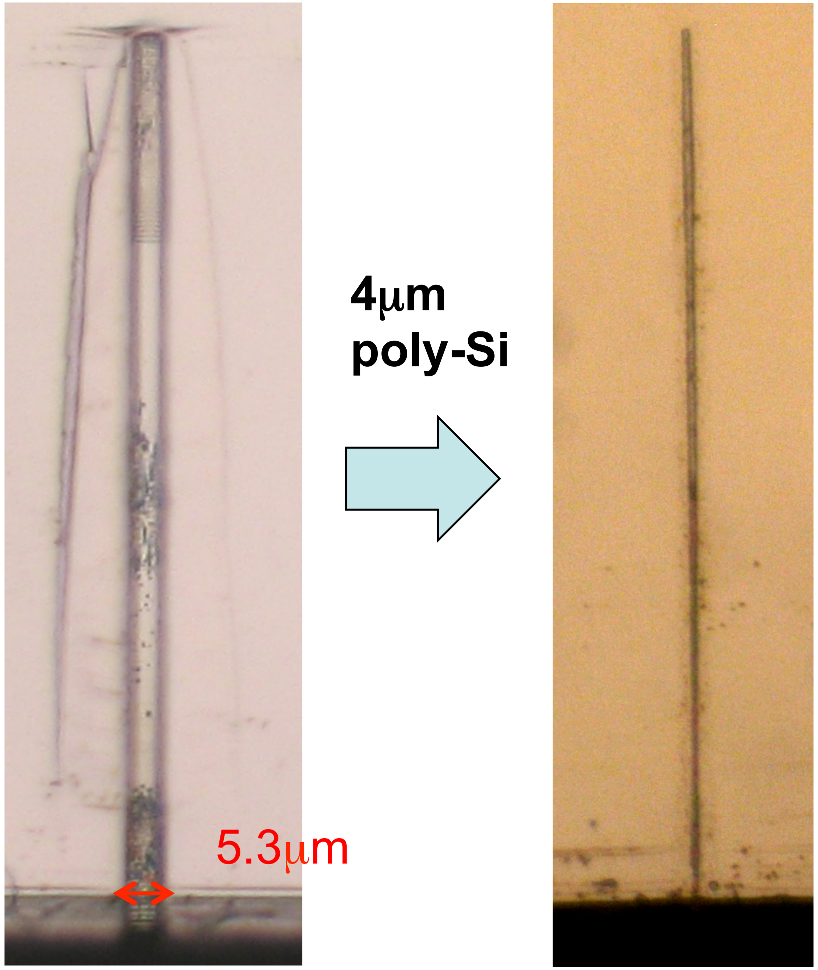
Junction columns optimized for uniformity

Testing different etching depth and etching through oxide layer for SOI approach

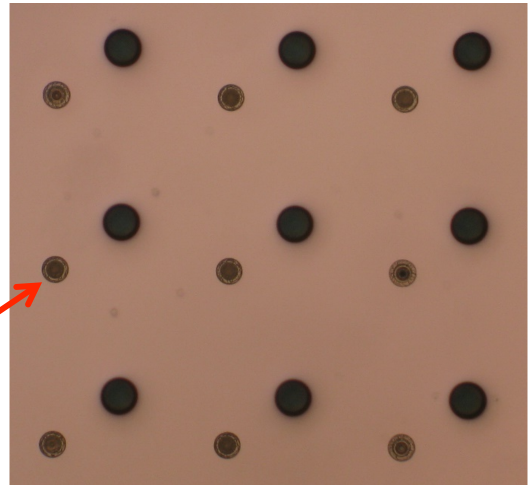


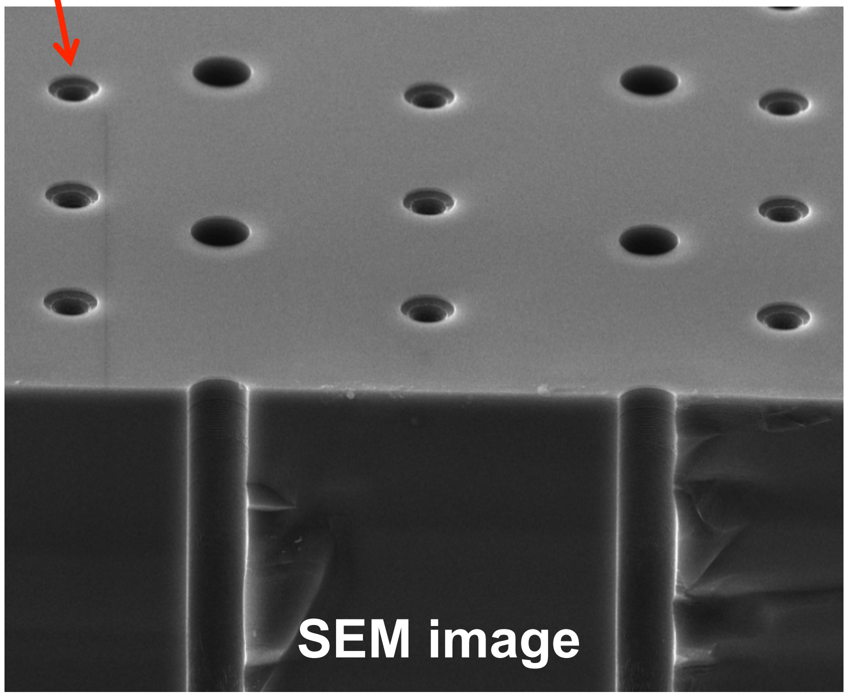
Poly-Si filling and 2nd DRIE

Reducing the hole diameter with poly-Si deposition
to ease the 2nd DRIE on the same wafer side



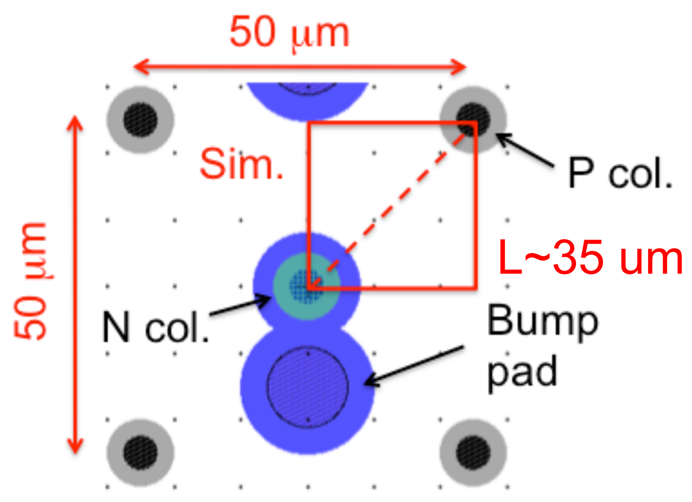
First holes partially filled with poly-Si



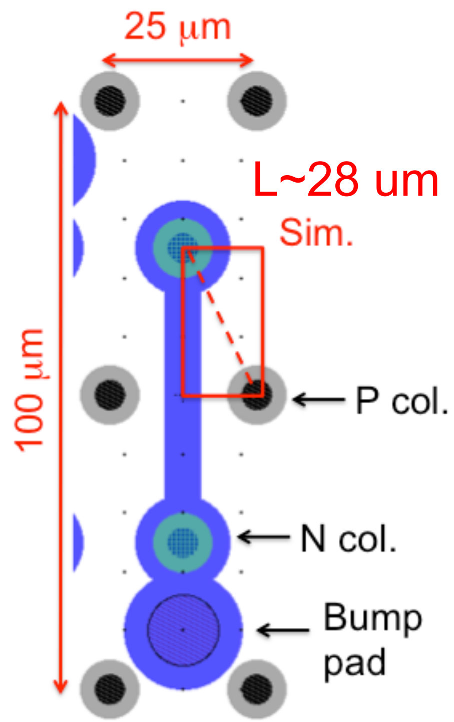


New 3D pixels: design and simulations

50 x 50

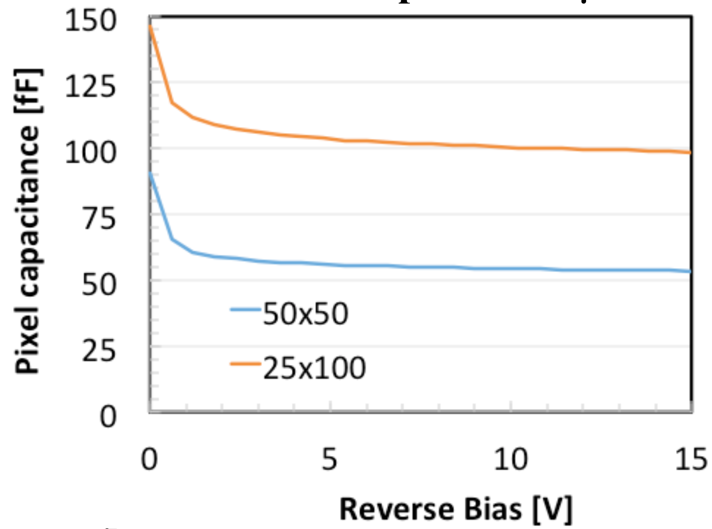


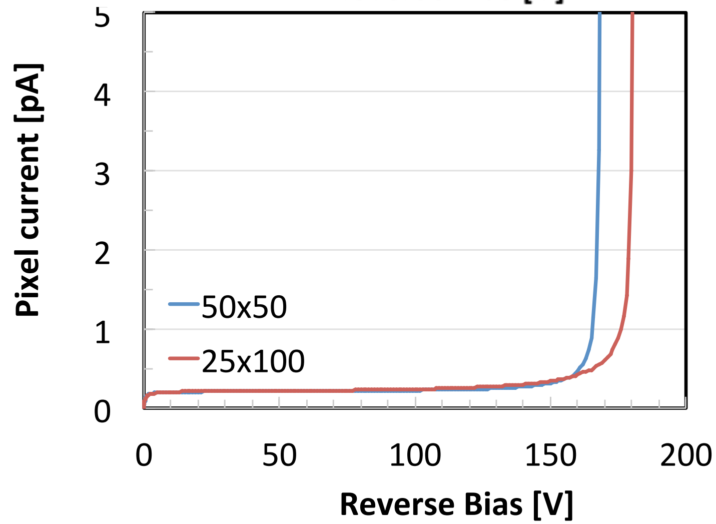
25 x 100



All designs assuming a column diameter of 5 µm

Thickness = 150 µm
N+ col. depth = 130 µm

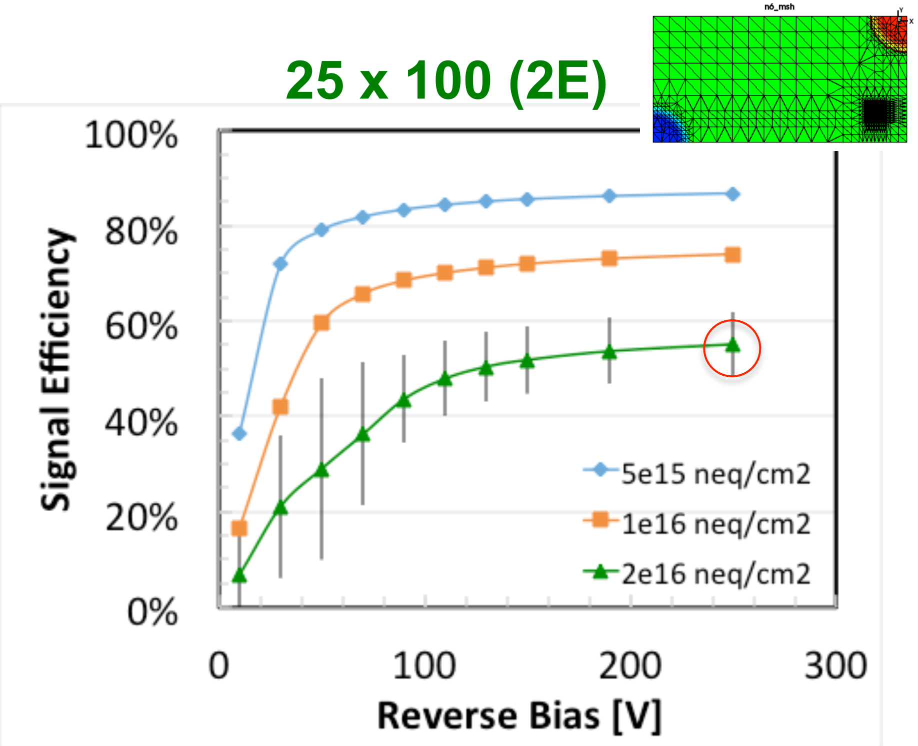




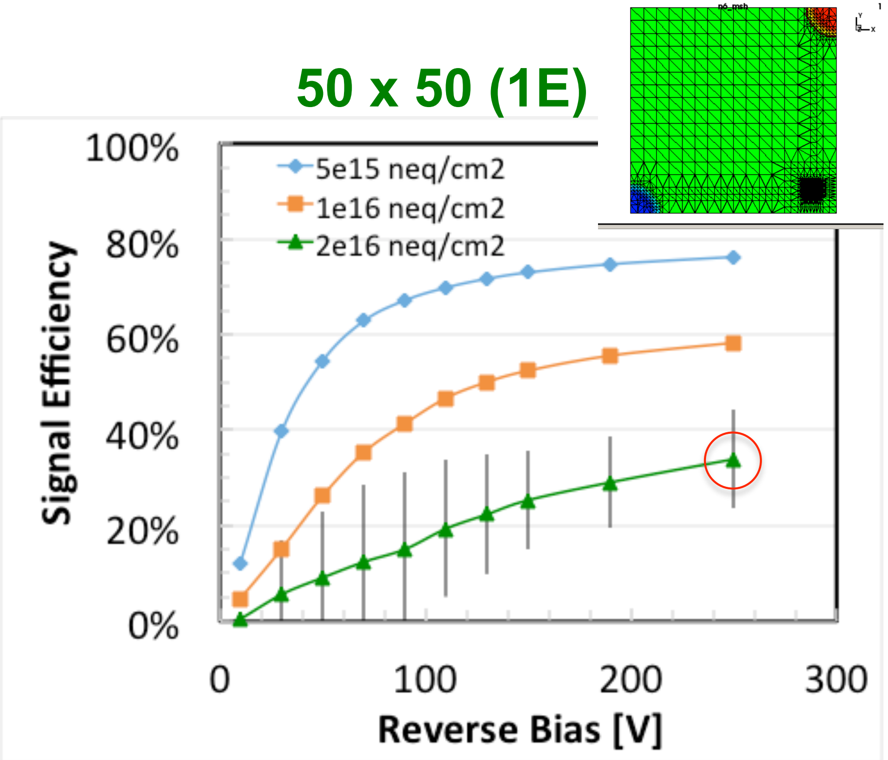
- 50x50 design safe, 25x100 is difficult … too little clearances (new ideas for bump pad to be tested)
- Capacitance compatible with RD53 specs
- Initial breakdown voltage high enough

Simulated signal efficiency (preliminary)

25 x 100 (2E)



50 x 50 (1E)



- 3-trap level "Perugia" model, parameters from D. Pennicard, NIMA 592 (2008) 16

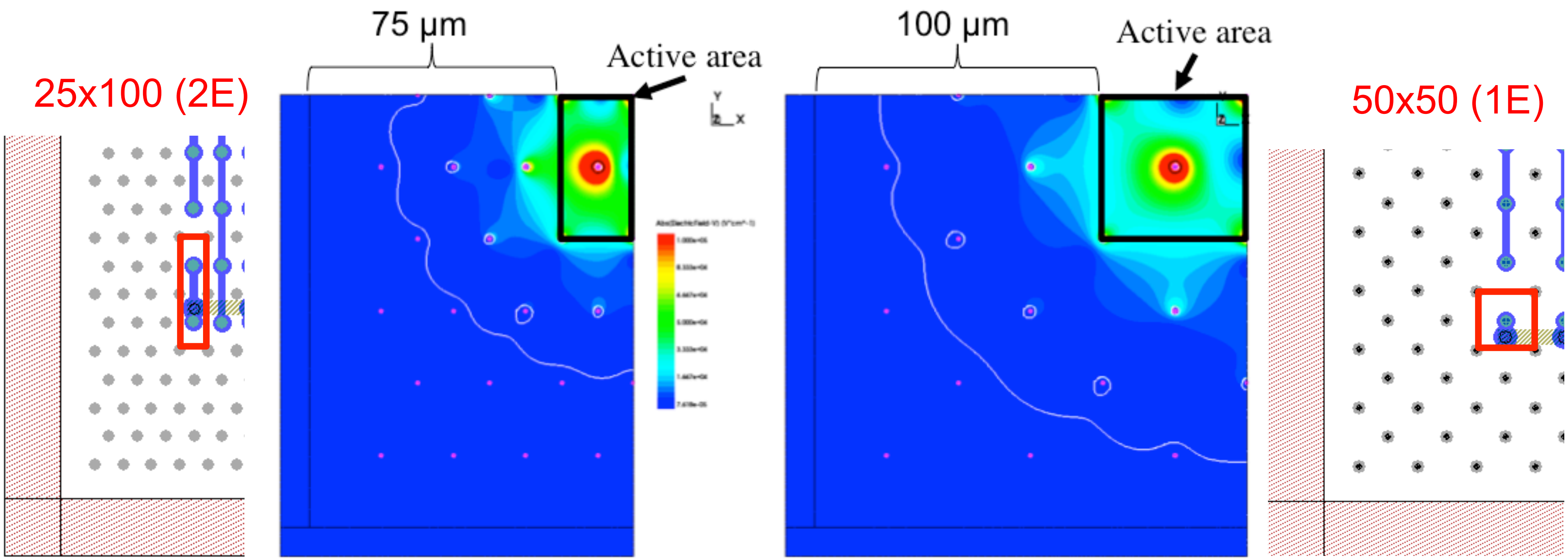
[Underestimates SE at large fuence, improved model required → Poster by D.Passeri]

- 1 μm thick (~2d) slice, with MIP vertical hits at several different points
- 20-ns integration of current signals, average, and normalization to injected charge
- Higher Signal Efficiency at lower V_{bias} in 25x100 (2E), as expected due to smaller L

Slim edges

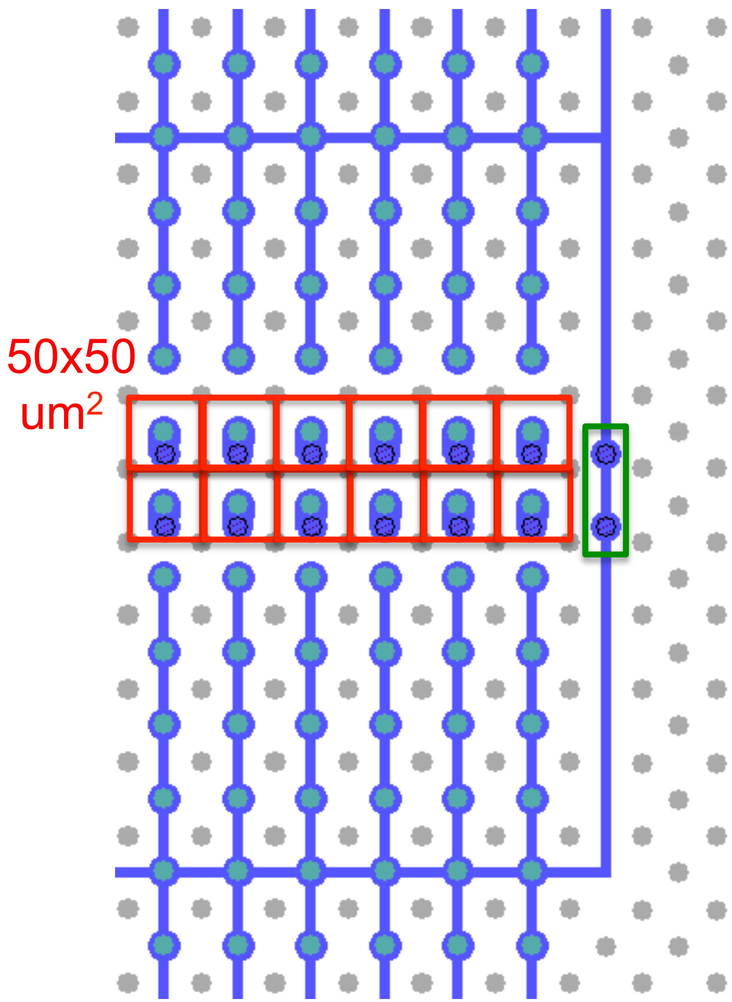
- Slim edge concept based on multiple ohmic columns termination developed for IBL (~200 μm) M. Povoli et al., JINST 7 (2012) C01015
- It can be made slimmer by reduced inter-electrode spacing

  (safely 75 - 100 μm, more aggressively down to ~50 μm)
- 3D guard rings also possible with similar dead area

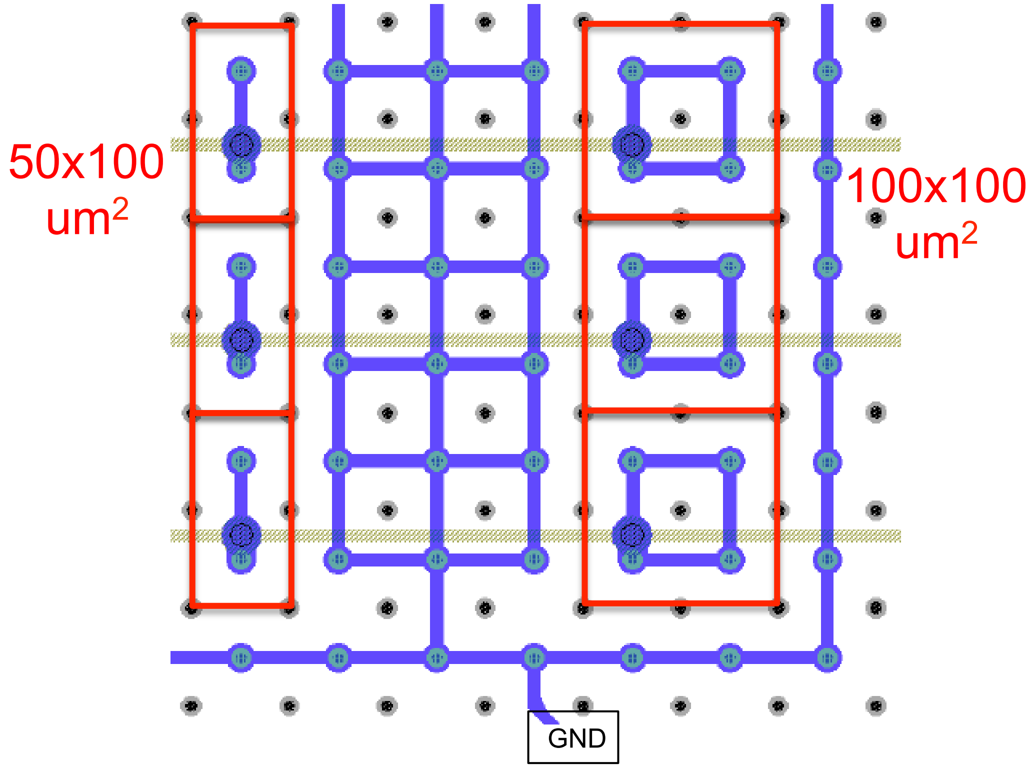


New pixels with existing ROCs ?

ATLAS FE-I4 50x50 (1E) + grid

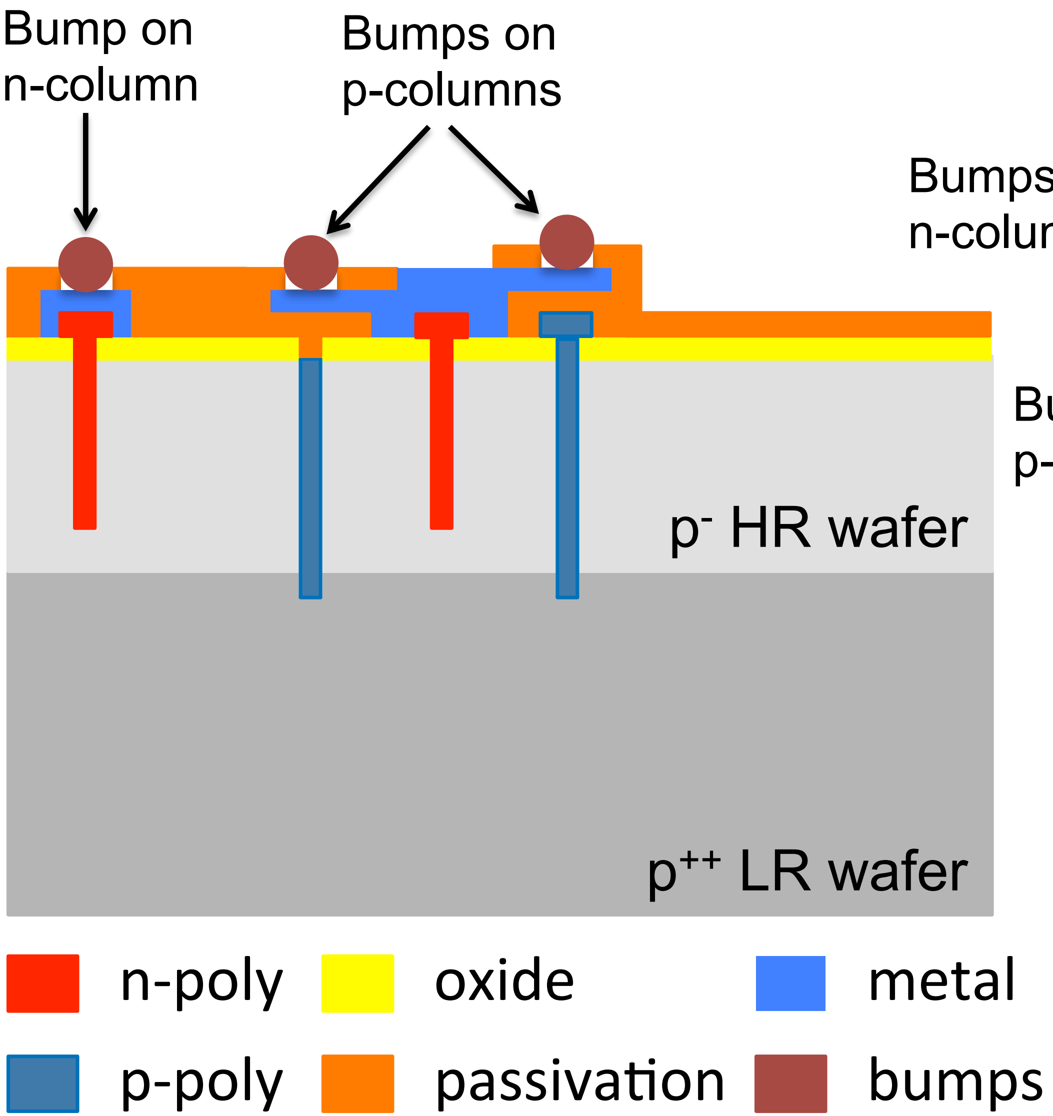


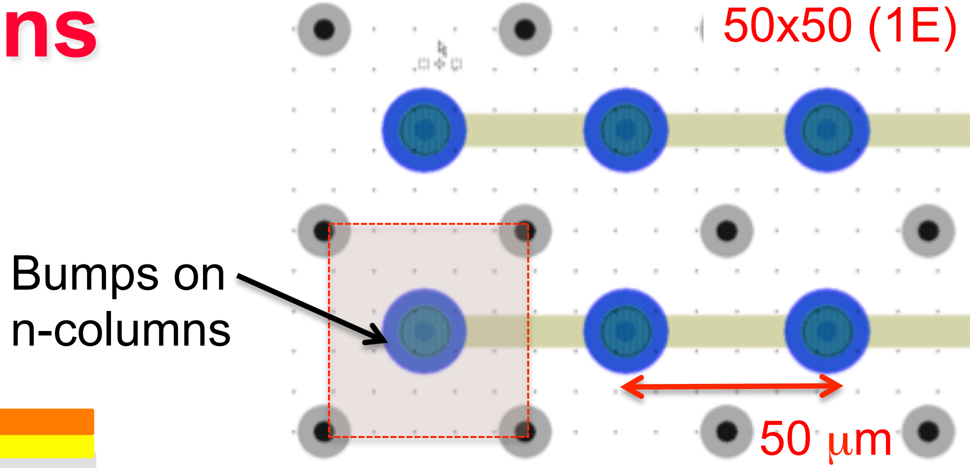
CMS PSI46: 50x50 (2E+4E) + grid

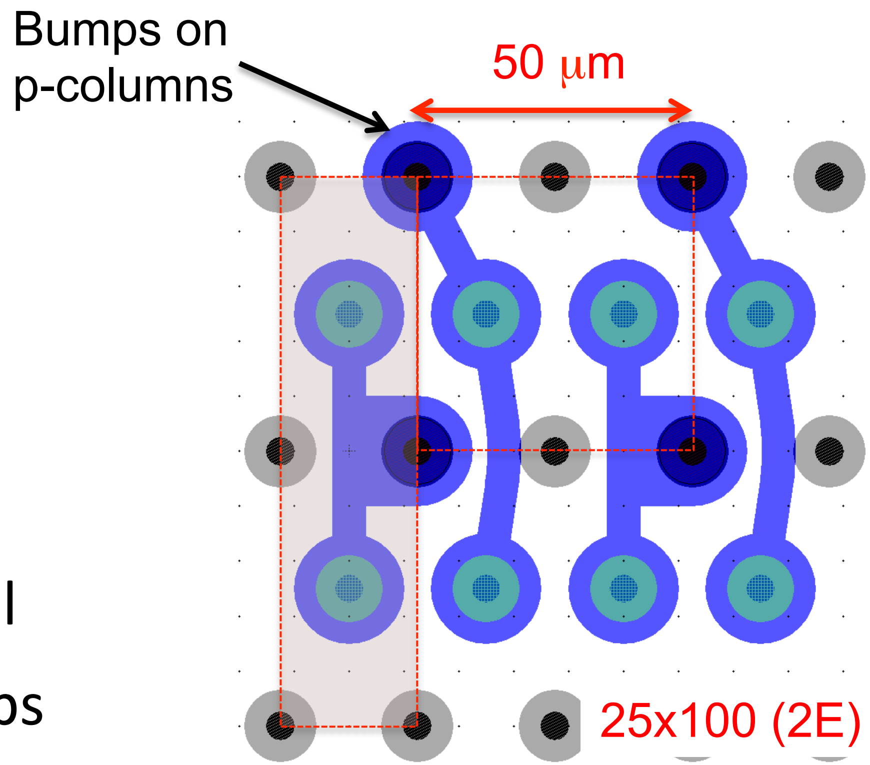


Small pixels take all bonding pads + rest of pixels at GND using a metal grid and extra-pads at the periphery

Bumps on columns

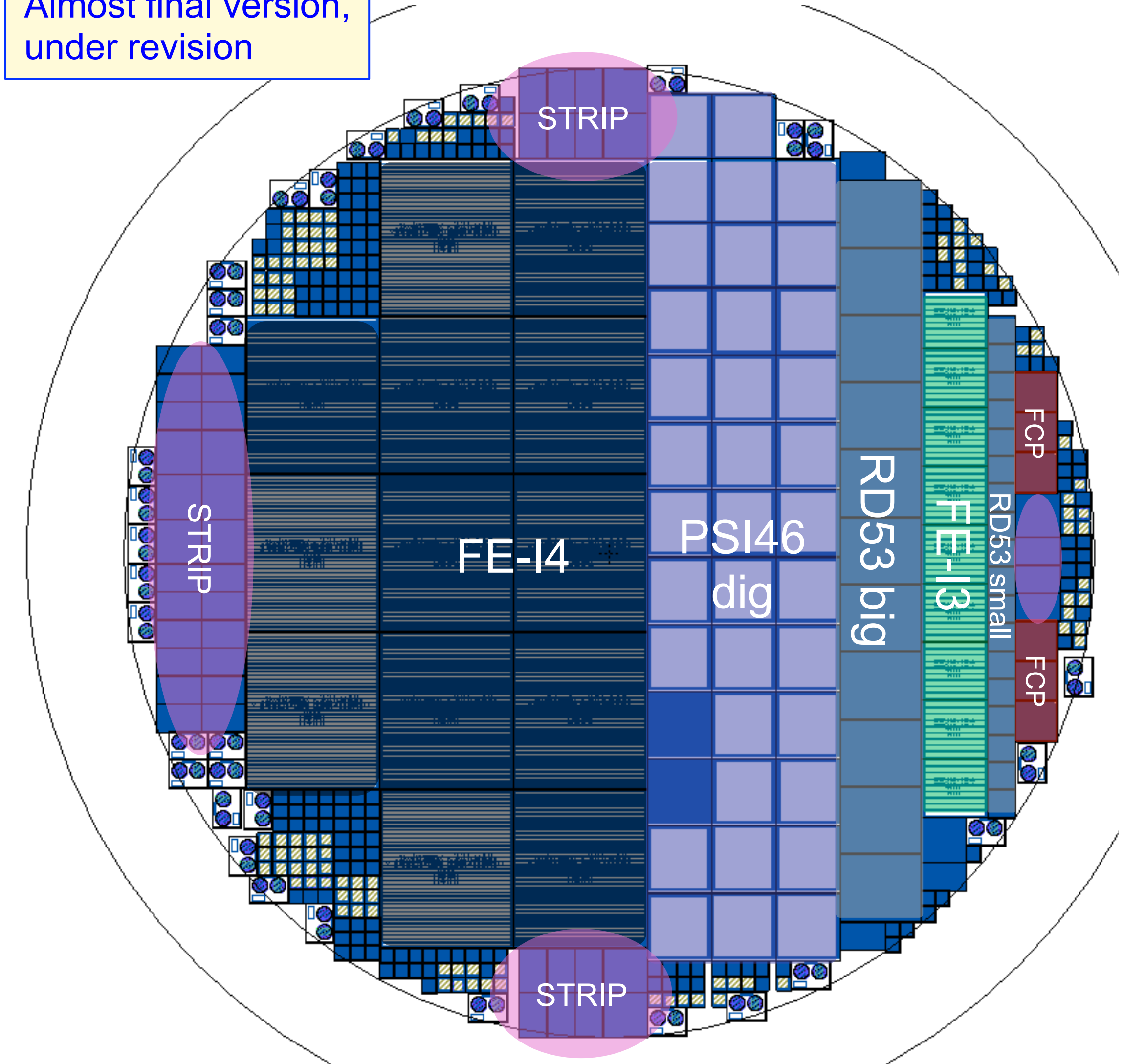






3D Pixel Wafer Layout

Almost final version, under revision



+ Test structures (strip, diodes, etc)

Many different pixel geometries and pitch variations:

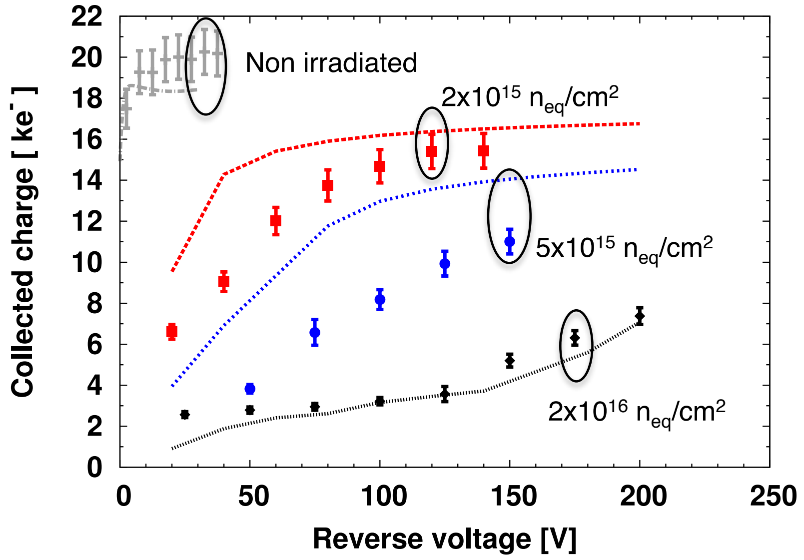
- FE-I4
  - 50 x 250 (2E) std
  - 50 x 50 (1E)
  - 25 x 100 (1E and 2E)
  - 25 x 500 (1E)
- FE-I3
  - 50 x 50 (1E)
  - 25 x 100 (1E and 2E)
- PSI46dig
  - 100 x 150 (2E and 3E) std
  - 50 x 50 (1E and 2E)
  - 50 x 100, 100 x 100 (2E + 4E)
  - 50 x 100, 100 X 150 (2E + 6E)
  - 25 x 100 (1E and 2E)
- FCP
  - 30 x 100 (1E)
- RD53
  - 50 x 50 (1E)
  - 25 x 100 (1E)
  - 25 x 100 (2E)

Conclusions

- A 3-years R&D program funded by INFN CSN1 is under way to push 3D and PAE pixel technology towards HL-LHC requirements
- An ATLAS-CMS-FBK synergy can give a unique opportunity for technical leadership in the most demanding inner-most tracking layers of HL-LHC detectors
- Initial results from technological tests are encouraging
- Now ready to start a batch of new 3D sensors
- Design/layout of PAE batch is under way

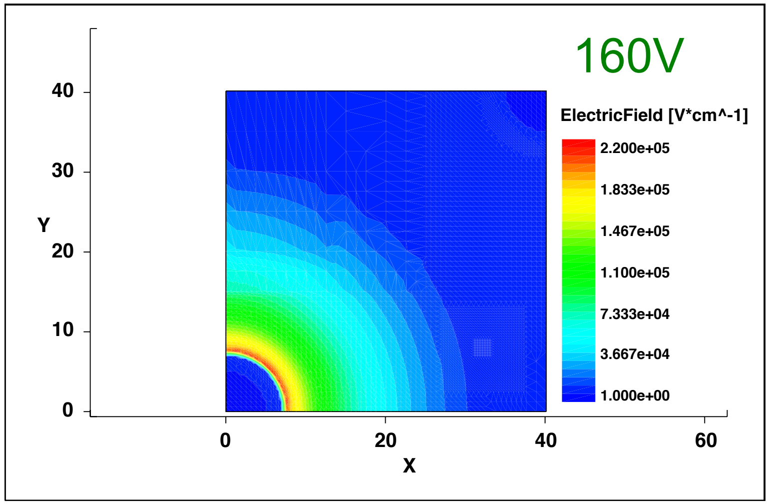
Back-Up Slides

Looking at large fluences with 3D strips



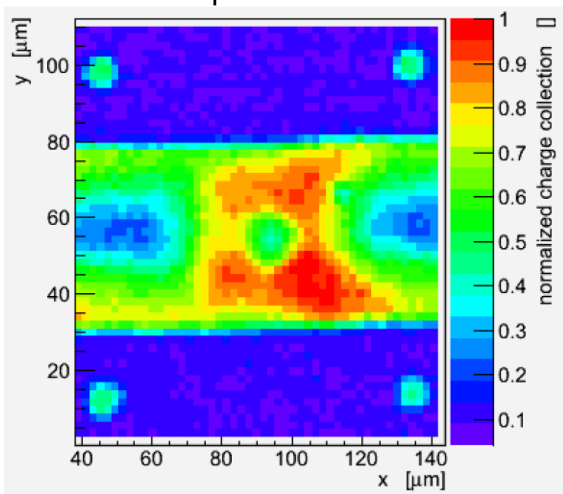
G.F. Dalla Betta et al, NIMA 765 (2014) 155

- Strip sensors from IBL prod. with ALIBAVA read-out
- Proton irradiation at KIT up to $2x10^{16}$ n_{eq}/cm^2
- Beta and laser tests performed in Freiburg
- Very good CCE, but clear saturation of the signal only for $2x10^{15}$ n_{eq}/cm^2
- For $2x10^{16}$ n_{eq}/cm^2 the bias voltage is not high enough to ensure uniform response.
- Simulated electric field fails to describe the double junction effect



Simulated electric field

$2x10^{16}$ n_{eq}/cm^2, 150V



Measured Laser signal

Performance comparison

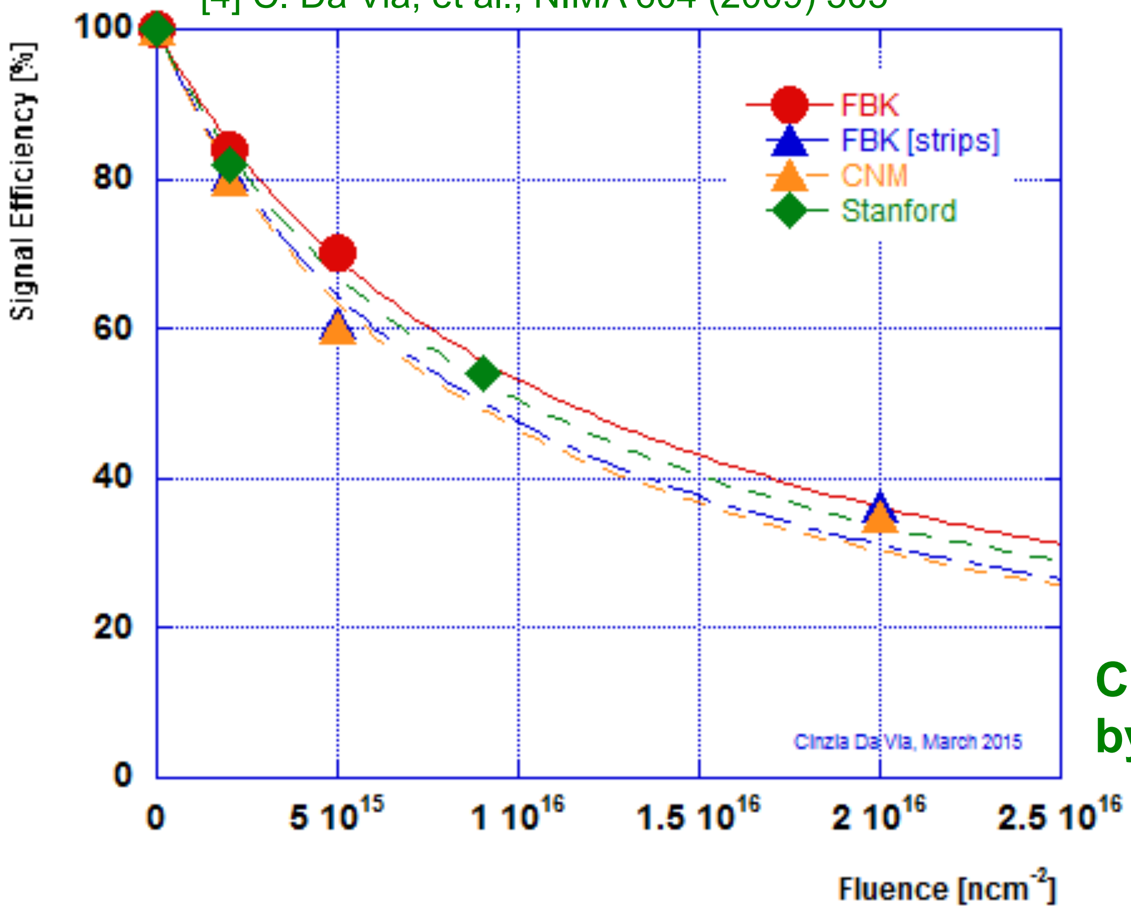
Data from:

[1] ATLAS IBL Collaboration, JINST 7 (2012) P11010

[2] G.-F. Dalla Betta, et al., NIMA 765 (2014) 155

[3] M. Koehler et al. NIMA 659 (2011) 272

[4] C. Da Via, et al., NIMA 604 (2009) 505



Signal Efficiency = Ratio of max. signal after irradiation and before irradiation

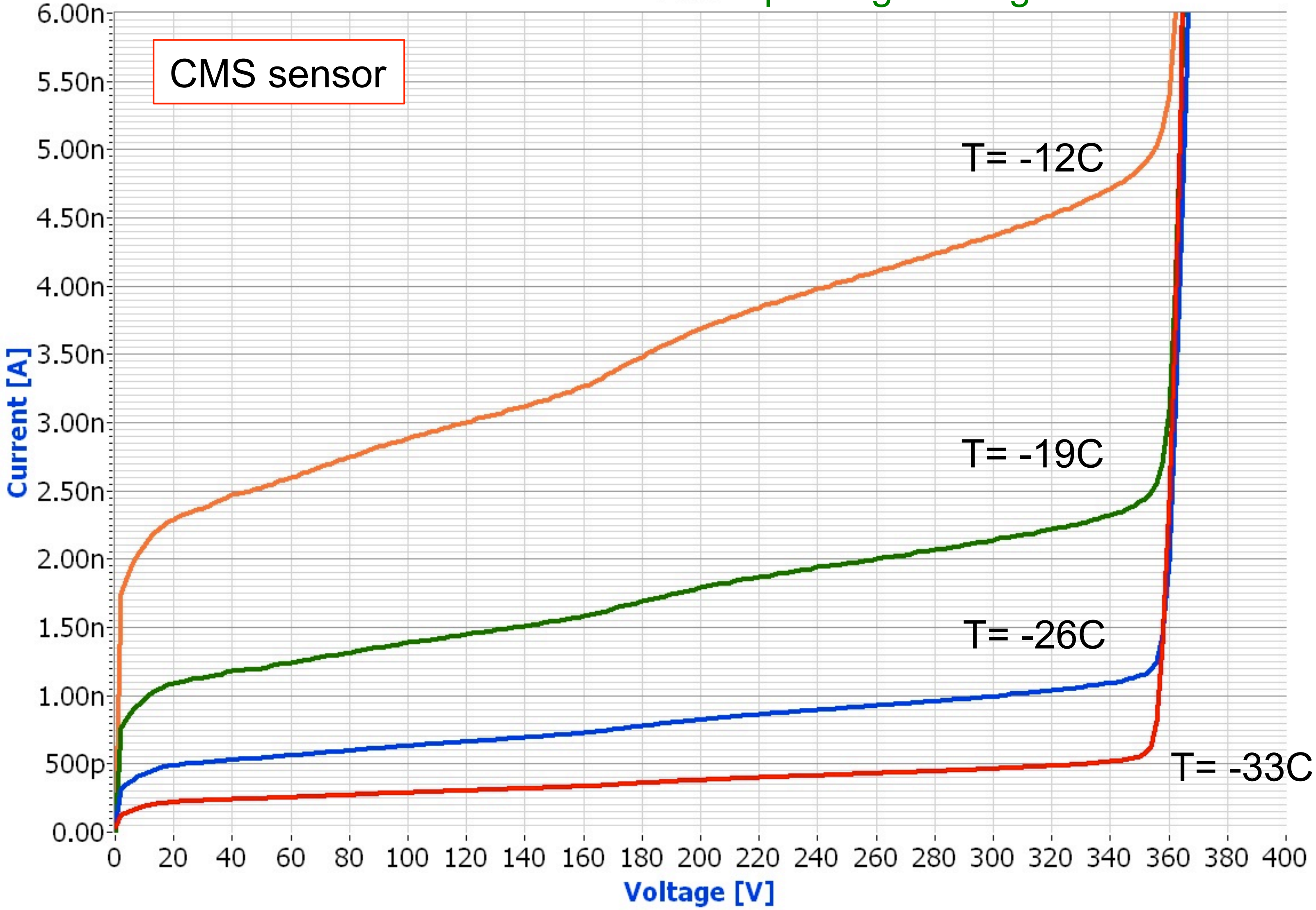
$$\boxed{SE = \frac{1}{1 + 0.6L\dfrac{K_\tau}{v_D}\Phi}}$$

C. Da Via, S. Watts, NIMA 603 (2009) 319

Compilation by C. Da Via

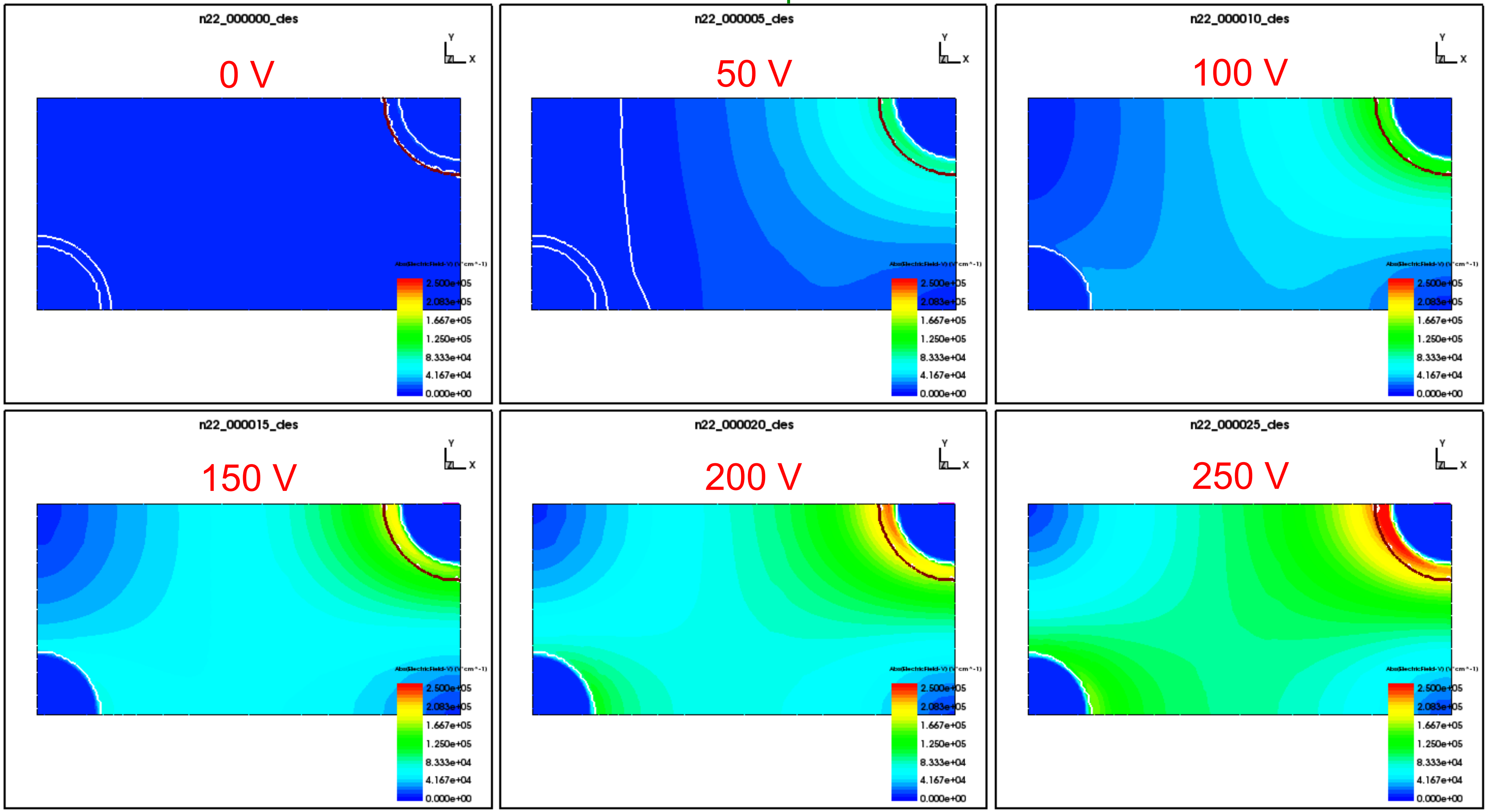
Pixel sensors I-V measurements (3)

Measured at INFN Firenze up to high voltage



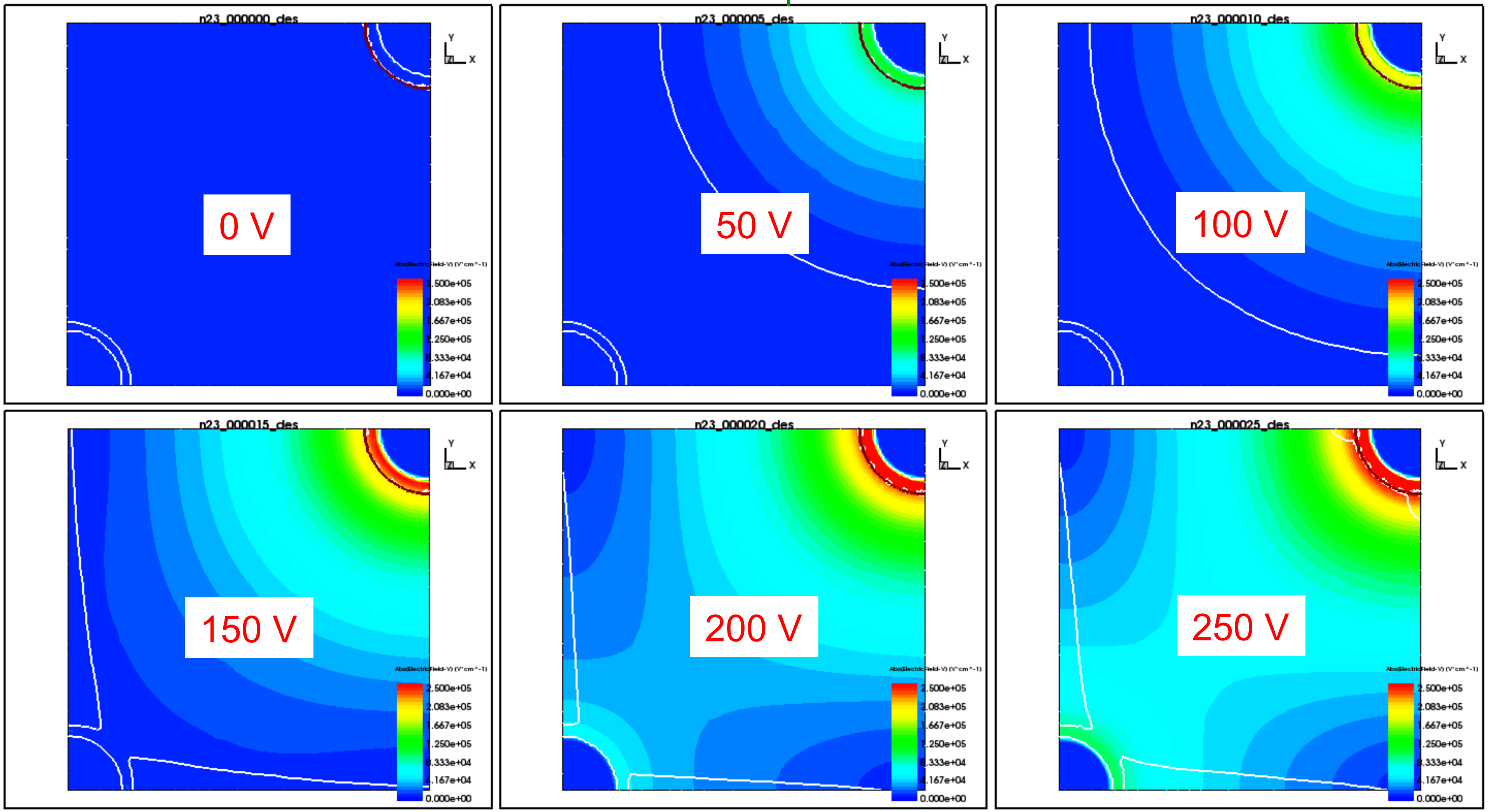
25x100: electric field 2d (preliminary)

$2\times10^{16}\ n_{eq}/cm^2$



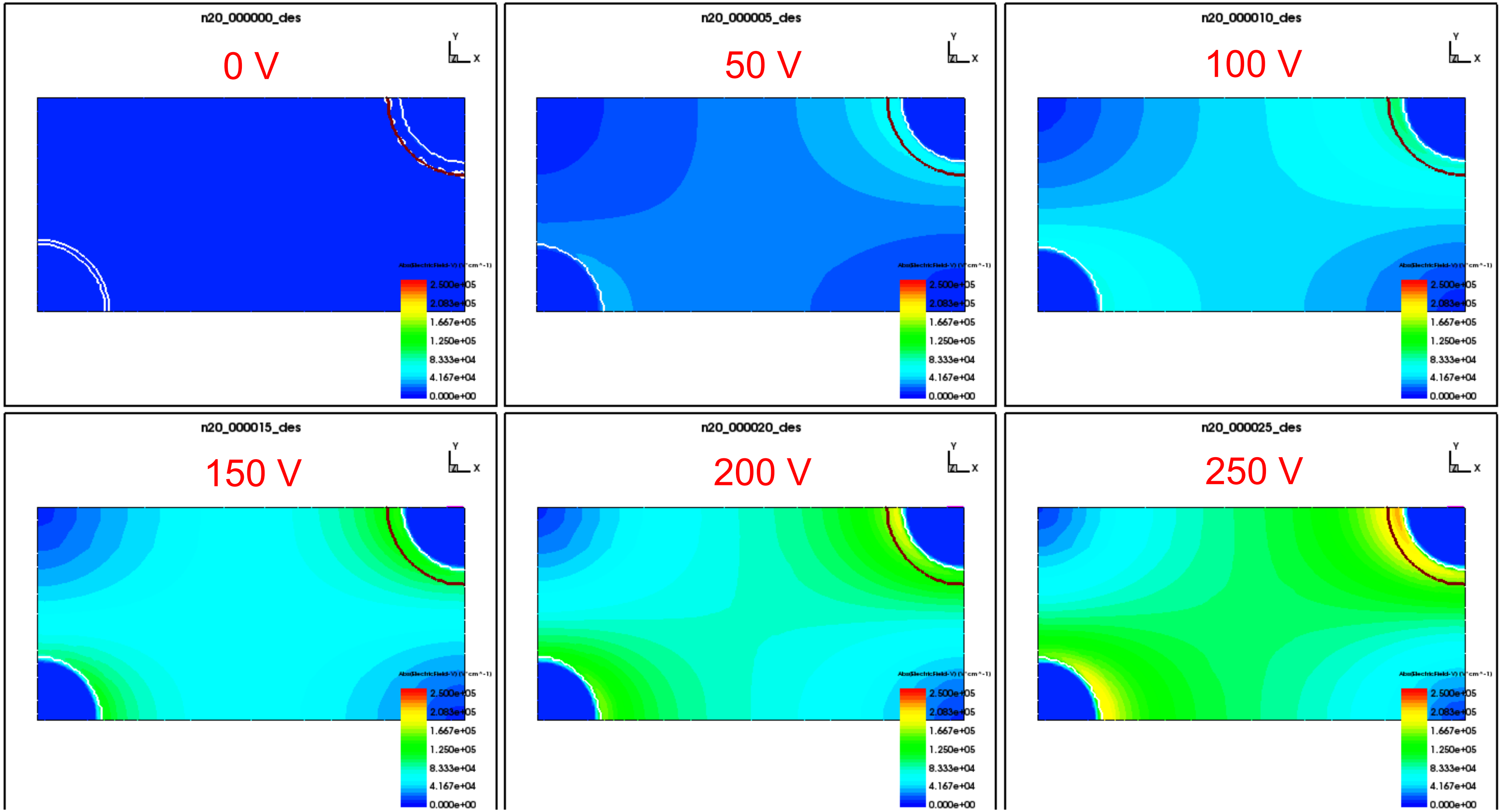
50x50: electric field 2d (preliminary)

$2x10^{16}$ n_{eq}/cm^2



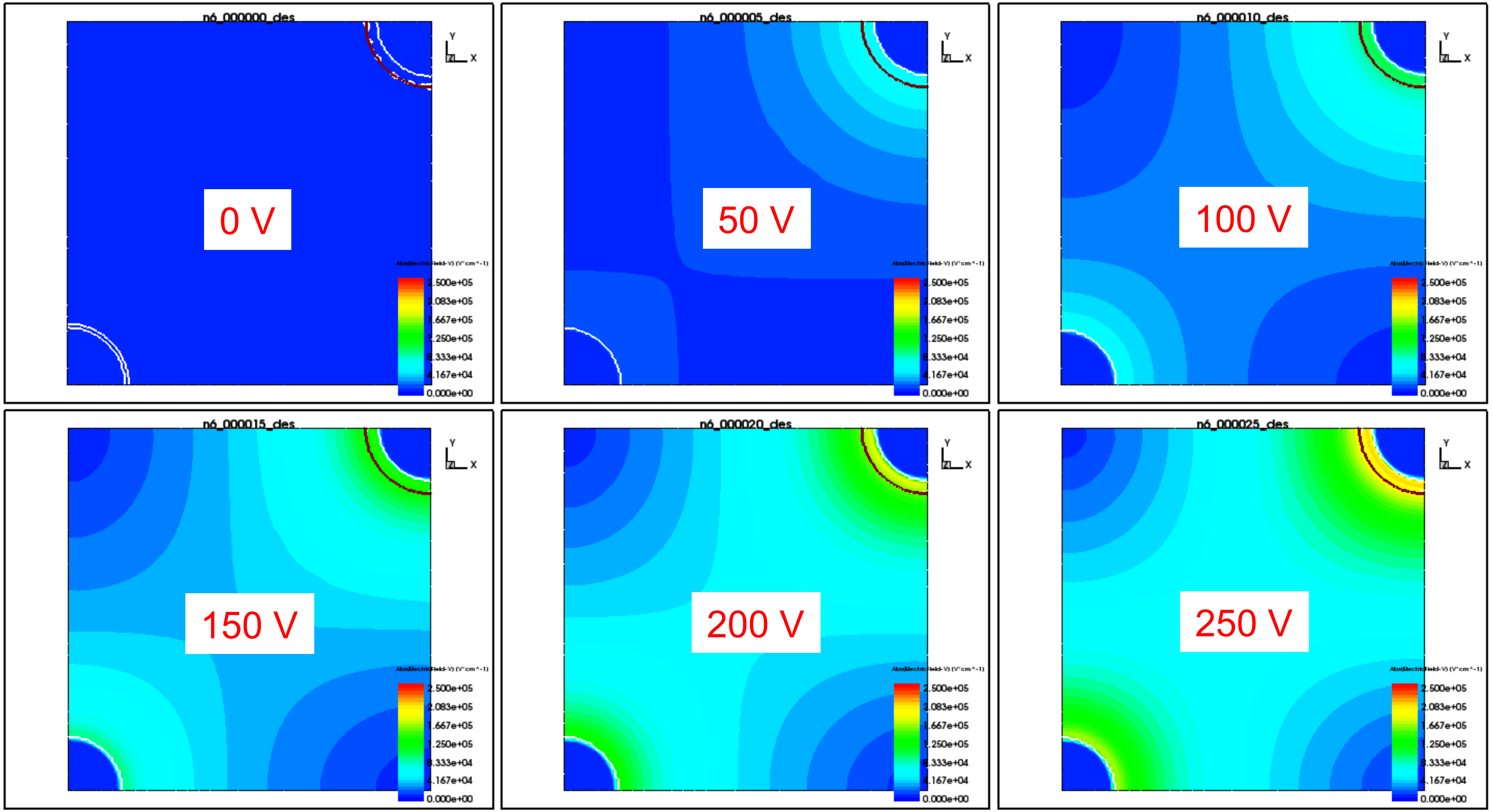
25x100: electric field 2d (preliminary)

$5 \times 10^{15}\ n_{eq}/cm^2$



50x50: electric field 2d (preliminary)

$5 \times 10^{15}\ n_{eq}/cm^2$



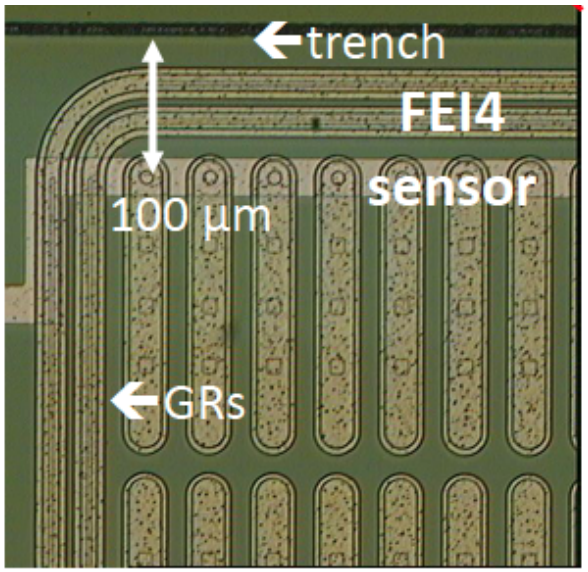
Active edge: design issues

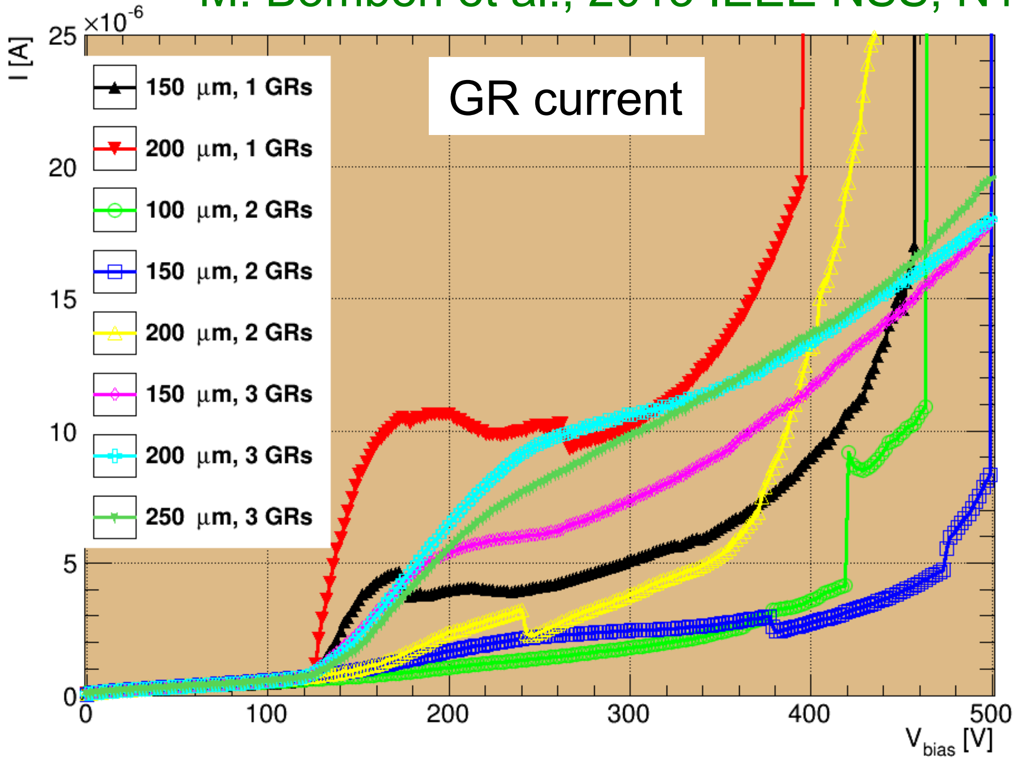
- Trade-off between dead area at the edge and breakdown voltage
- Previous experience (FBK-LPNHE): V_{bd} ~ 400 – 500 V for edge size of 100 – 200 μm after neutron irradiation at 2.5×10^{15} n_{eq} cm^{-2} (not annealed, tested at 0±1°C), it can be better with more ionizing dose
- Optimized guard ring designs

and p-spray dose implant

to be implemented

M. Bomben et al., 2013 IEEE NSS, N13-2





Improved radiation damage model

See Poster by D. Passeri et al. "Modeling of Radiation Damage Effects in Silicon Detectors at High Fluences HL LHC with Sentaurus TCAD"

- ✓ Goal: extend the predictive capabilities of a past radiation damage modeling to HL-LHC radiation damage levels (e.g. fluences > 2.0×10^{16} n_{eq} cm^{-2})
- ✓ Bulk radiation damage modelling: extension of the three-level UniPG modelling (capture cross section, charge multiplication, avalanche effects)
- ✓ Interface radiation damage modelling:
  - oxide fixed charge and interface trap state @fluence
  - systematic study of acceptor/donor states at different energies

Test structures from FBK and IMM irradiated with γ-rays up to 500 Mrad being characterized

- ✓ Simulations vs. measurements.
- ✓ Charge collection as a function of radiation fluences at T=248K, V_{BIAS}=900V
- ✓ Data from T. Affolder et al., NIMA, Vol. 623 (2010)