TREDI Workshop 2013

Testbeam and laboratory characterization of 3D CMS pixel sensors

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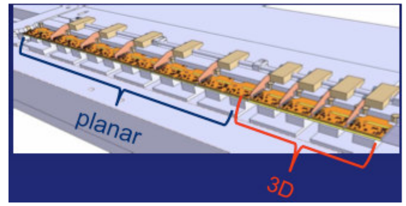
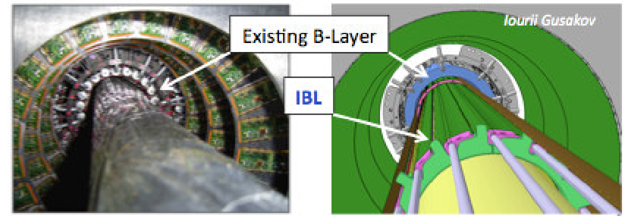
3Ds: APPLICATIONS AT LHC

3Ds are emerging as one of the most promising tracking detector candidates for future upgrades at LHC

25% of ATLAS IBL will be made of 3D sensors

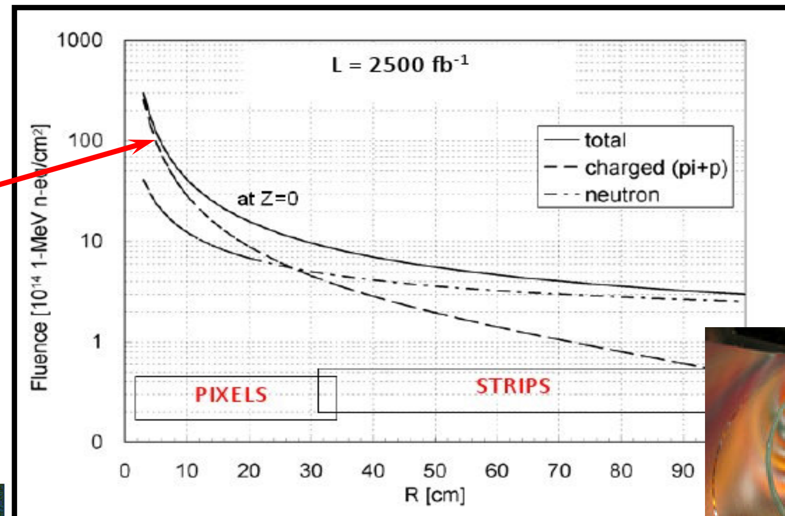


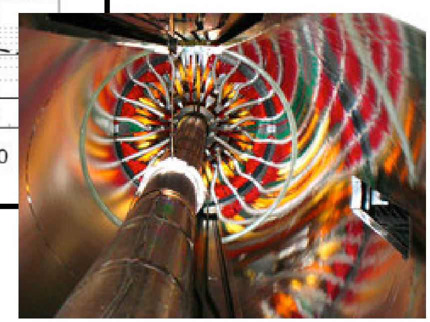


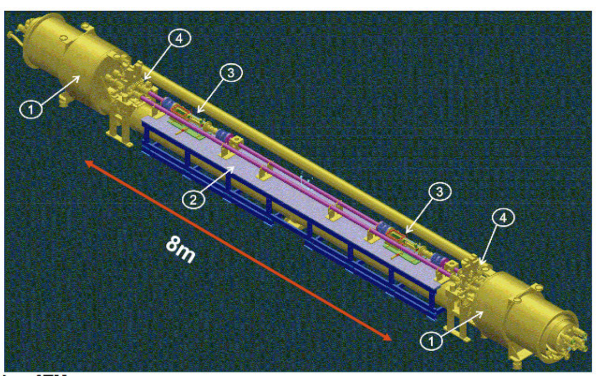
New rad-hard sensor candidates for the HL-LHC CMS vertex detector ($L = 10^{35} cm^{-2}s^{-1}$)

Equivalent dose $\sim 10^{16} n_{eq}/cm^2$ @ r = 5 cm

Current pixel detector can operate up to a fluence of $\sim 6x10^{14} n_{eq}/cm^2$







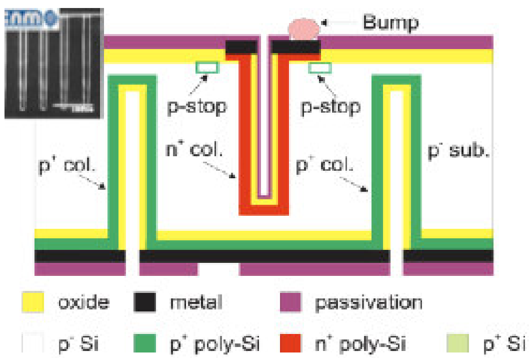
HPS (near beam proton spectrometer - under approval for CMS)

Crucial requirement for this application: radiation hardness and active edges

3D PRODUCTIONS

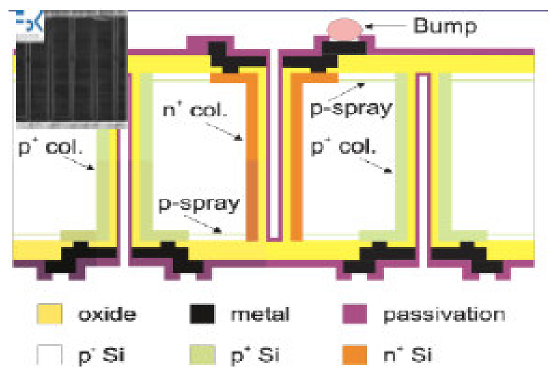
- First 3D fabricated at Stanford Nanofabrication Facility, then manufacturing technology transferred to Sintef (Norway)
- Thanks to the ATLAS 3D Collaboration, in 2007 a common effort among different processing facilities started: Stanford, Sintef, FBK (Italy), CNM (Spain)

Existing 3D designs:



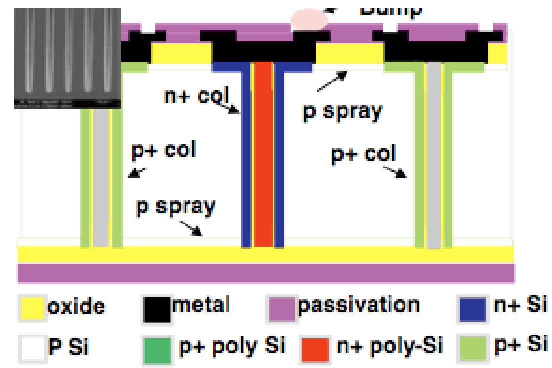
Double side, not passing through columns but slim edges (200 µm)

CNM
(First FBK production)



Double side full 3D with slim edges (200 µm)

Latest FBK production



Single side, full 3D with active edges requires a support wafer which is removed later

Sintef and Stanford

3D PRODUCTIONS

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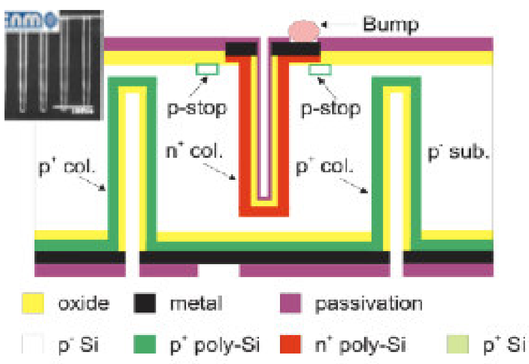
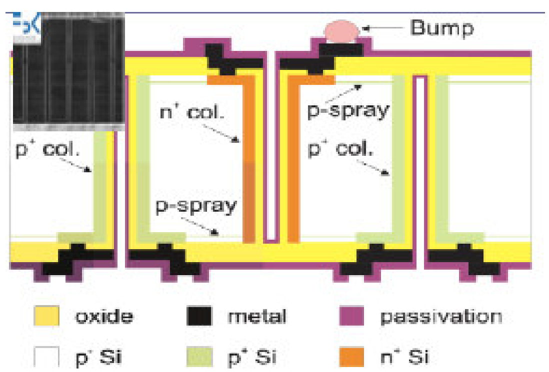
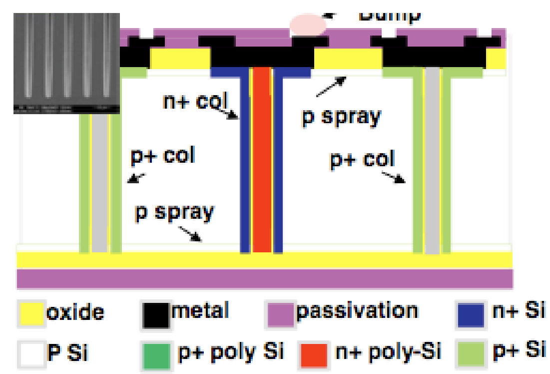
Existing 3D designs:





Double side full 3D with slim edges (200 μm)



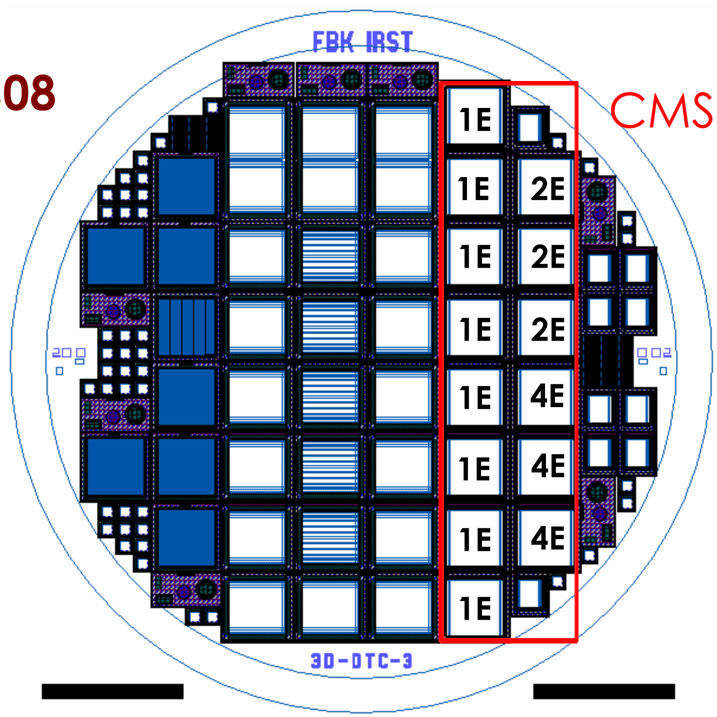
Sensors fabricated on p-type silicon wafer.
n+ (readout) electrodes and p+ (ohmic) electrodes etched from opposite sides of the wafer. Both of them are left hollow.

CMS 3D SENSORS IN FBK BATCHES

CMS sensor: 52*80 pixels — Pixel size: 100*150 μm^2
Passing through columns

ATLAS08	ATLAS09
Wafer thickness: 200 μm	Wafer thickness: 230 μm
Standard edges (1 mm)	Slim edges (200 μm)

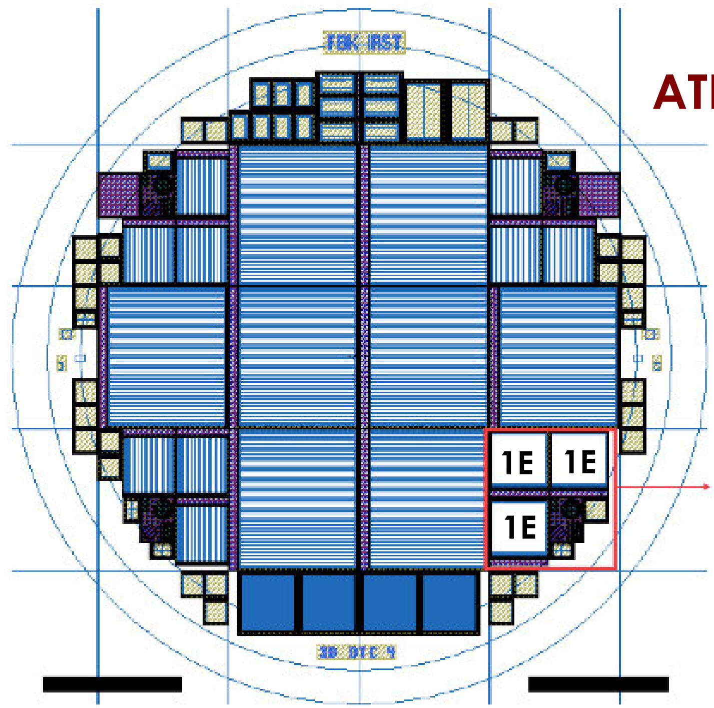
ATLAS08



CMS

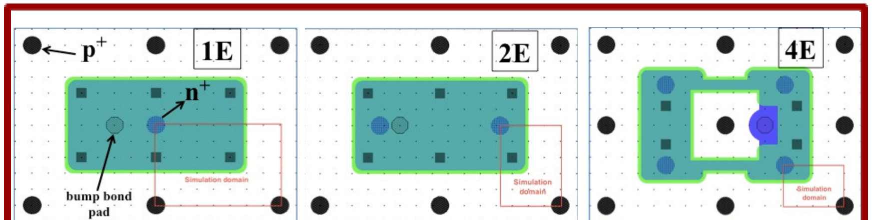
2 wafers bump-bonded (W8,W3)

ATLAS09



CMS

1 wafers bump-bonded

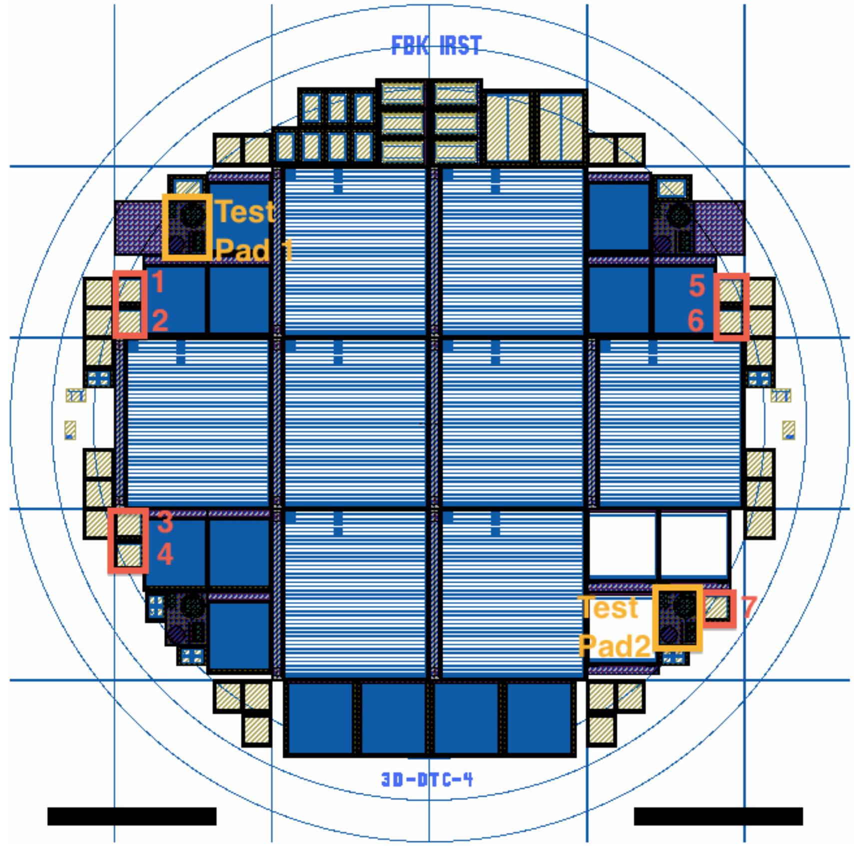


Inter-electrode distance: 90 μm (1E), 62.5 μm (2E), 45 μm (4E)

ATLAS10

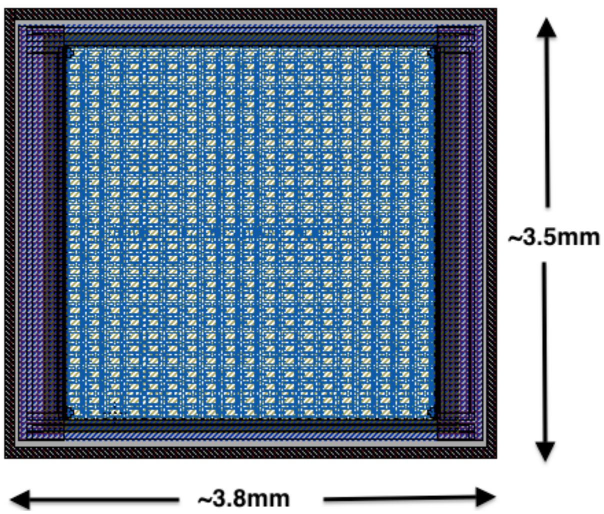
CMS-1E diodes only (in **red**)

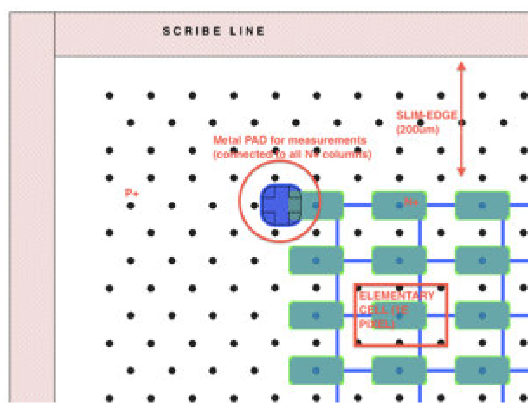
Test structures (in **orange**)



CMS-1E diodes:

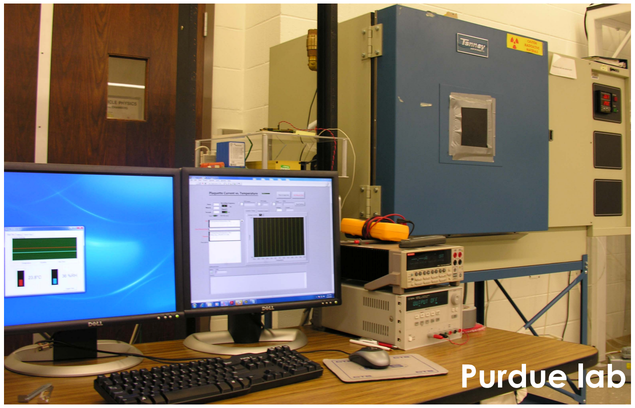
- 3.5 x 3.8 mm^2
- 19 x 29 pixels
- 200 ± 20 µm thickness





CMS 3D TESTING FACILITY

- Sensors bump-bonded at Selex Sistemi Integrati (solder material: indium) to the existing CMS readout chip (ROC) PSI46



3Ds wire-bonded to the test board and characterized in Purdue, FNAL and Torino

Results of IV curves, noise measurements and source tests presented here (published in **JINST 7 (2012) P08023**)

- Test beam with 120 GeV/c proton at FNAL Meson Area
- Irradiation with 800 MeV proton at LANSCE

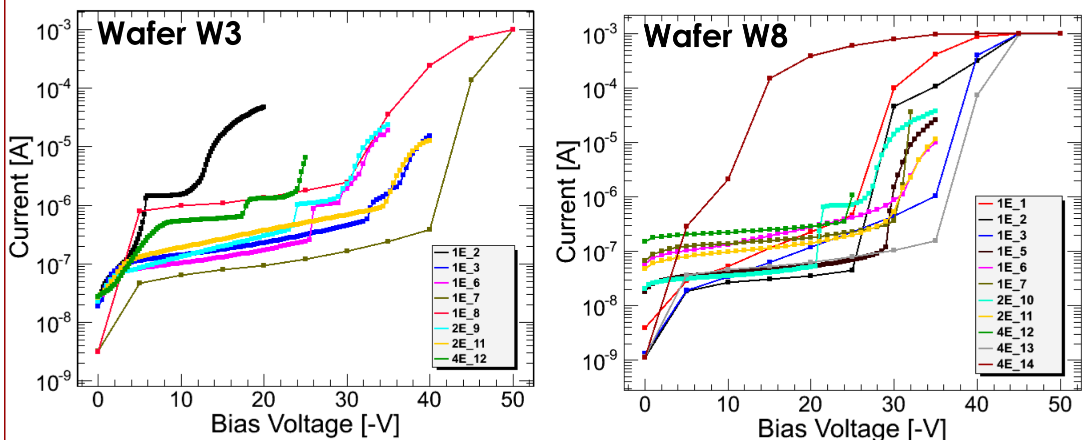
Preliminary results before and after irradiation with different fluences presented here

LABORATORY TEST: IV MEASUREMENT

IV curves measured in lab at room temperature (before irradiation)

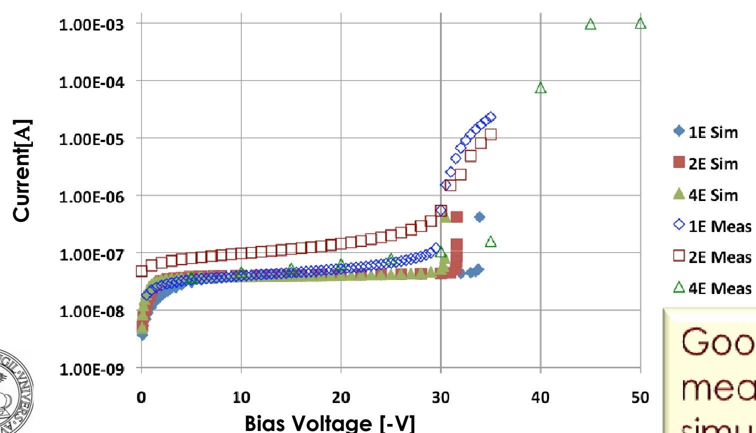
ATLAS08

Measured IV curves



Typical current: 100 nA-1μA
Depletion voltage: ~5 V
Breakdown voltage: 25-40 V

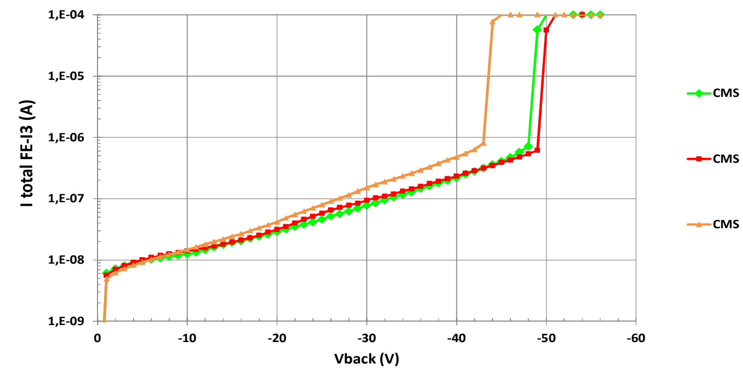
Simulated and measured IV curves



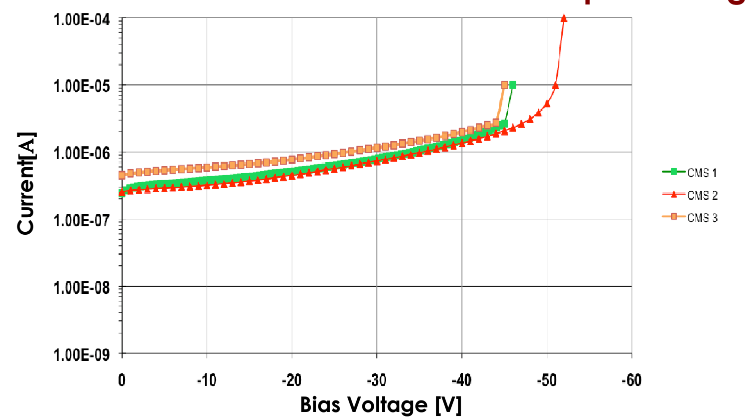
Good agreement between measurements and simulation

ATLAS09

On wafer electrical test performed at FBK



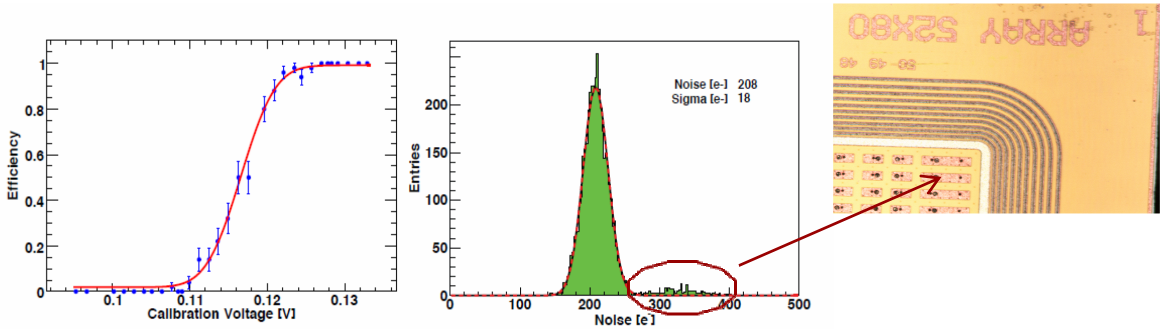
IV curves measured after bump-bonding



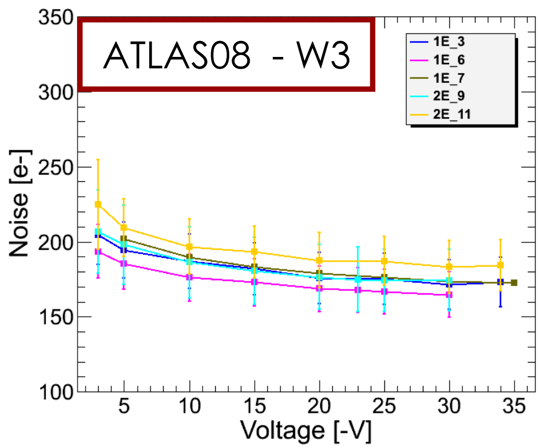
Higher breakdown voltage with respect to ATLAS08

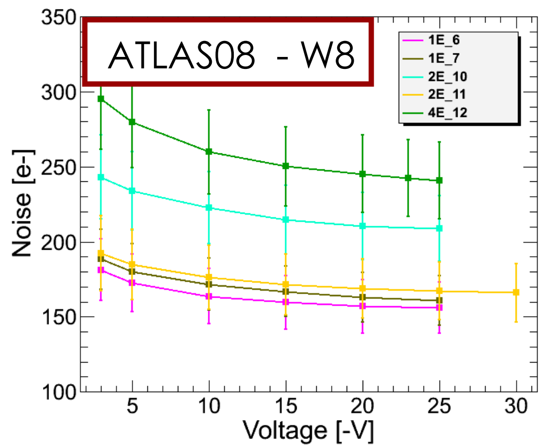
LABORATORY TEST: NOISE MEASUREMENT

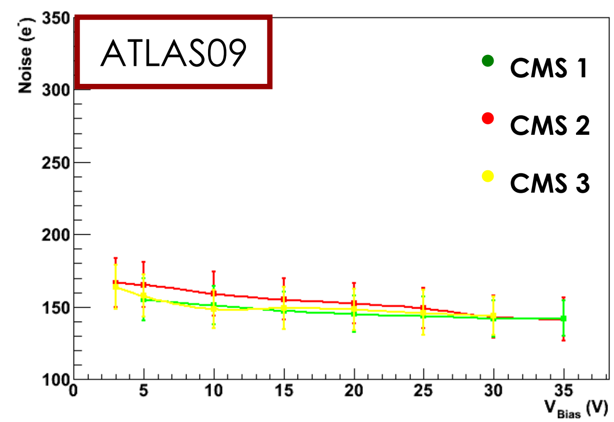
Noise measurement from S-curve (room temperature)



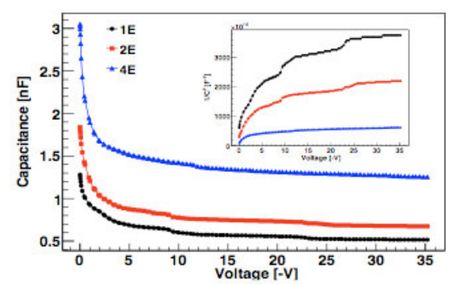
Typical noise for CMS planar sensors: 100 -150 e-







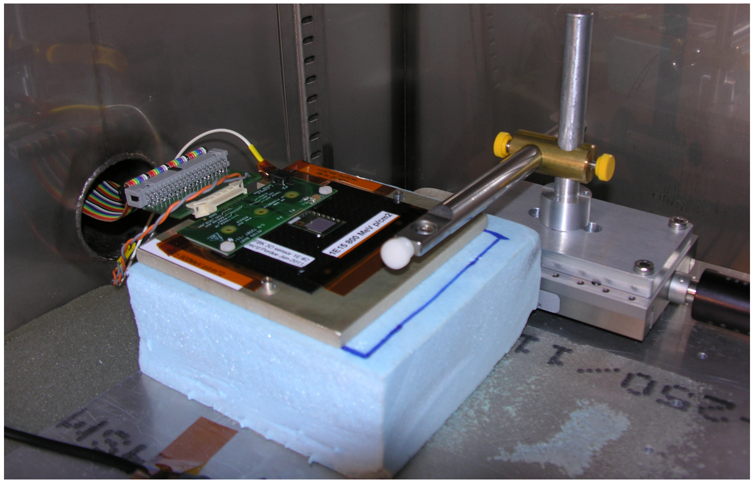
Noise vs V_{bias}
Noise decreases as reverse bias increases as expected from CV behaviour
Noise increases with electrode number



Simulated capacitance for 3Ds with different electrode configurations

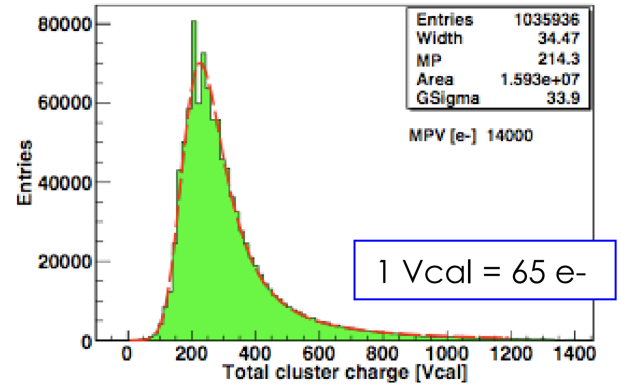
LABORATORY TEST: COLLECTED CHARGE

Source test setup - Purdue

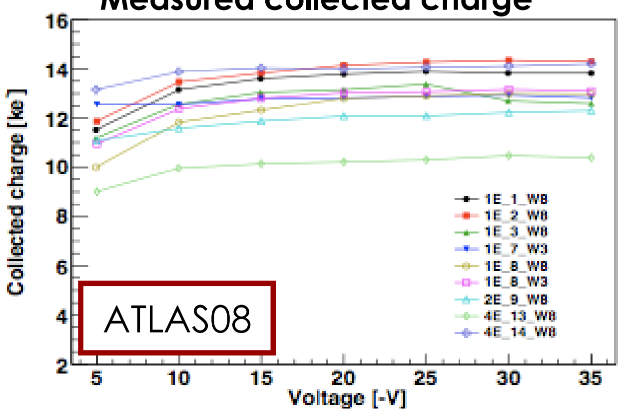


- Sr-90 source: 1 mCi, $E_\beta = 0.546$ MeV
- Sensor-source distance ~1cm. No collimator
- Room temperature
- Random trigger

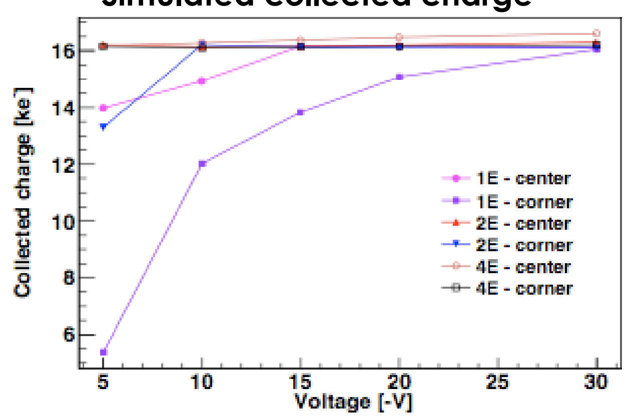
4E sensor - V_{bias} = -15V



Measured collected charge

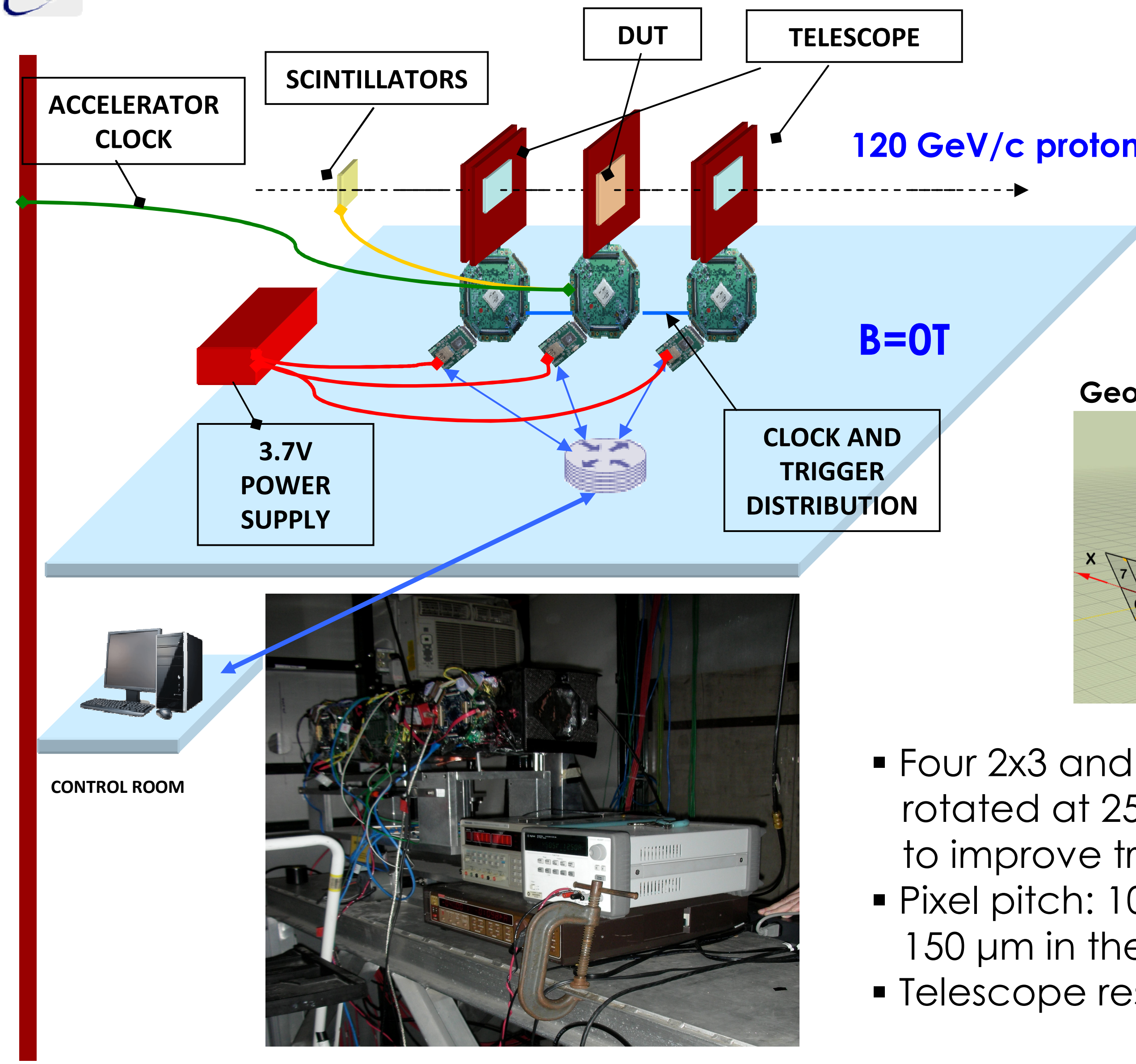


Simulated collected charge

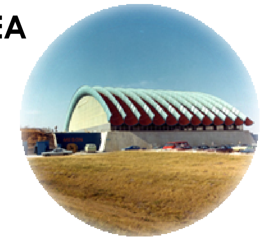


Measured collected charge slightly less than simulated one. Possible reasons:
- combined effect of charge sharing and readout chip threshold (~3.9 ke)
- wafer thickness uncertainty (200±20)μm

TEST BEAM SETUP

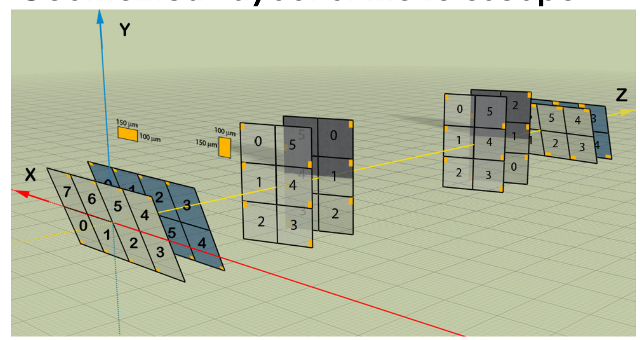


FNAL MESON AREA



Rotation and cooling system for DUT provided by Purdue

Geometrical layout of the telescope



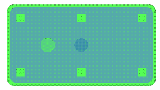
- Four 2x3 and four 2x4 CMS pixel modules rotated at 25° with respect to the beam to improve tracking resolution
- Pixel pitch: 100 μm along the rotated axis, 150 μm in the other direction
- Telescope resolution on DUT: 6 μm

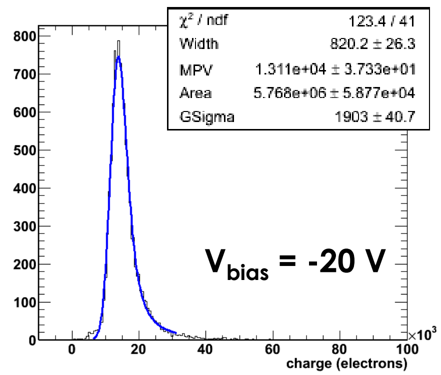
Alignment done with a software developed at Milano Bicocca

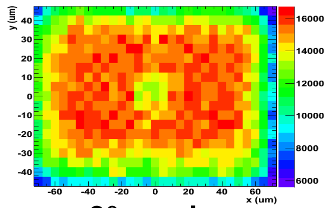
TEST BEAM PRELIMINARY RESULTS

ATLAS09 1E sensor

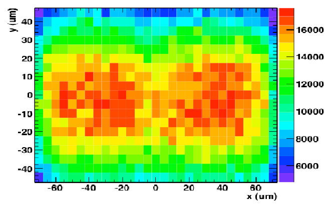
Charge collection







0° angle



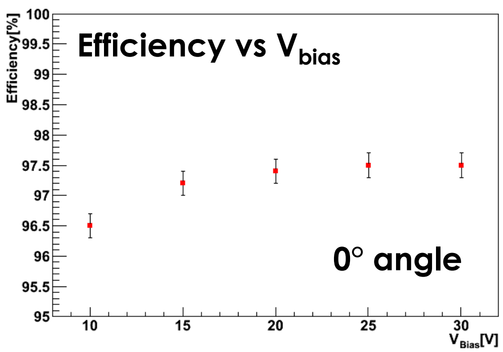
20° angle

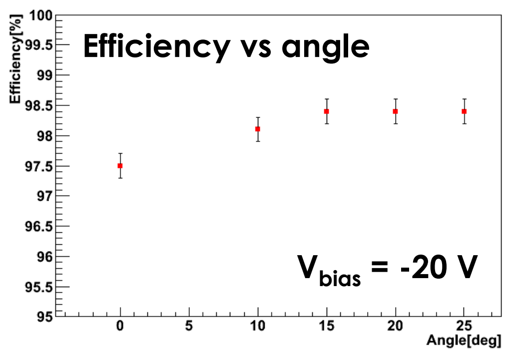
Charge collection
As expected in 230 μm thick silicon (~17 ke⁻); when the track hits the central part of the pixel; elsewhere reduced by the combined effect of charge sharing and readout chip threshold.

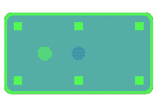
Efficiency
97.5% at 0°. Inefficiency partly explained by the electrodes being inactive volumes for track impinging orthogonal to the detector. It increases by tilting the sensor of 20° with respect to the beam

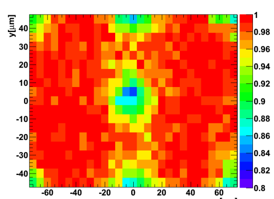
Spatial resolution
~11 (~13) μm in the best (worse) direction at 20°

Efficiency

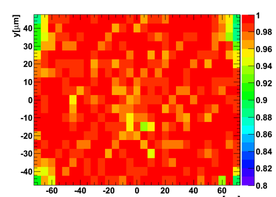








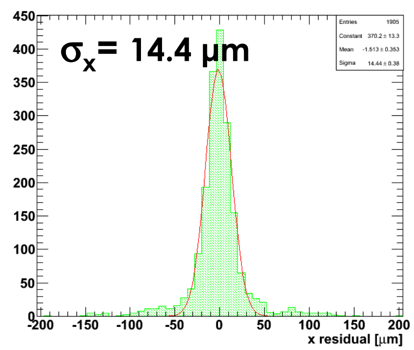
0° angle

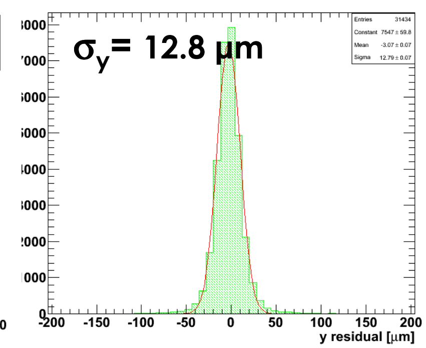


20° angle

Spatial resolution

Residuals for 2 pixel clusters





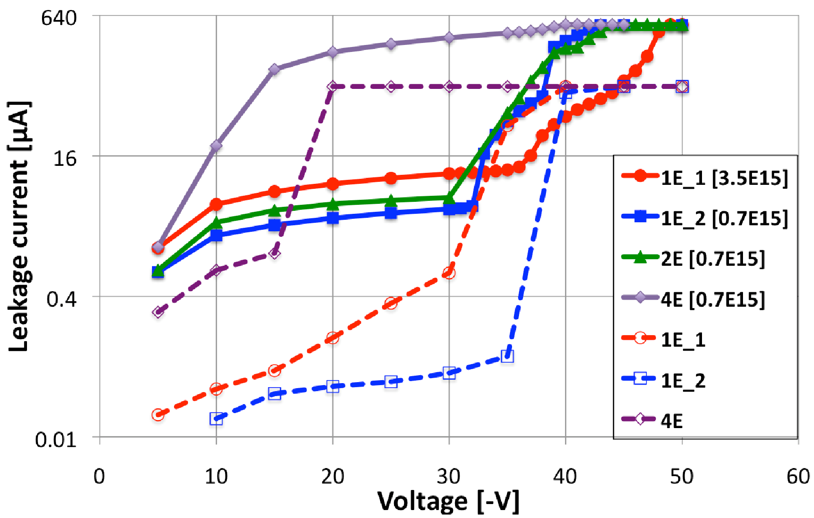
Analysis for other sensors is ongoing

IRRADIATION

- Performed at Los Alamos irradiation facility (LANSCE)
- 800 MeV protons
- 4 ATLAS08-W8 sensors irradiated (2x 1E, 1x 2E, and 1x 4E)
- Fluences:
  - $1 \cdot 10^{15}$ p/cm^2 ($0.7 \cdot 10^{15}$ n_{eq}/cm^2) → 1E_1
  - $5 \cdot 10^{15}$ p/cm^2 ($3.5 \cdot 10^{15}$ n_{eq}/cm^2) → 1E_2
  - $1 \cdot 10^{15}$ p/cm^2 ($0.7 \cdot 10^{15}$ n_{eq}/cm^2) → 2E
  - $1 \cdot 10^{15}$ p/cm^2 ($0.7 \cdot 10^{15}$ n_{eq}/cm^2) → 4E
- Sensors have been kept at -20 °C (no annealing)
- All test performed at -20°C
- Irradiation of ATLAS09 sensors ongoing

POST-IRRADIATION LABORATORY TEST: IV CURVES AND NOISE

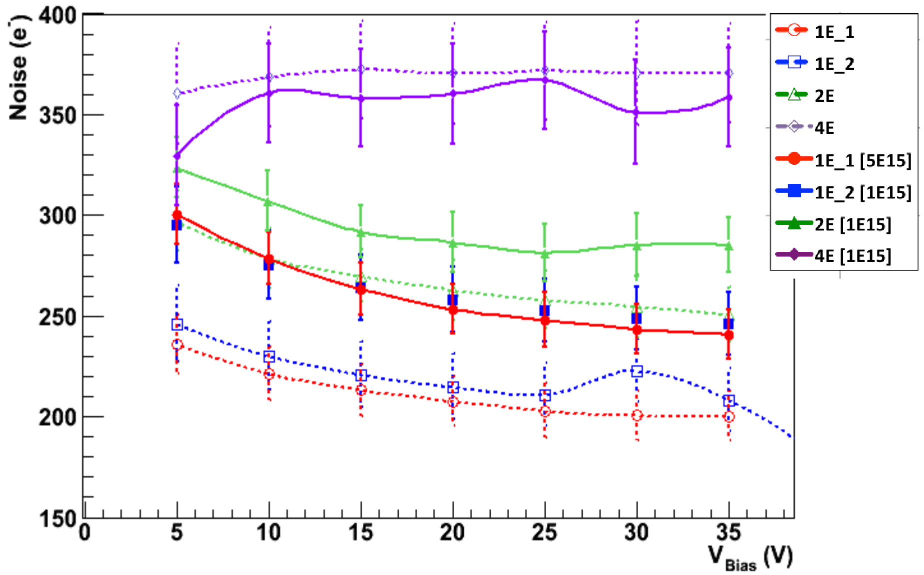
Pre-irradiation: room temperature
Post-irradiation: -20°C



Effect of irradiation on IV curves

Increase of breakdown voltage not as expected

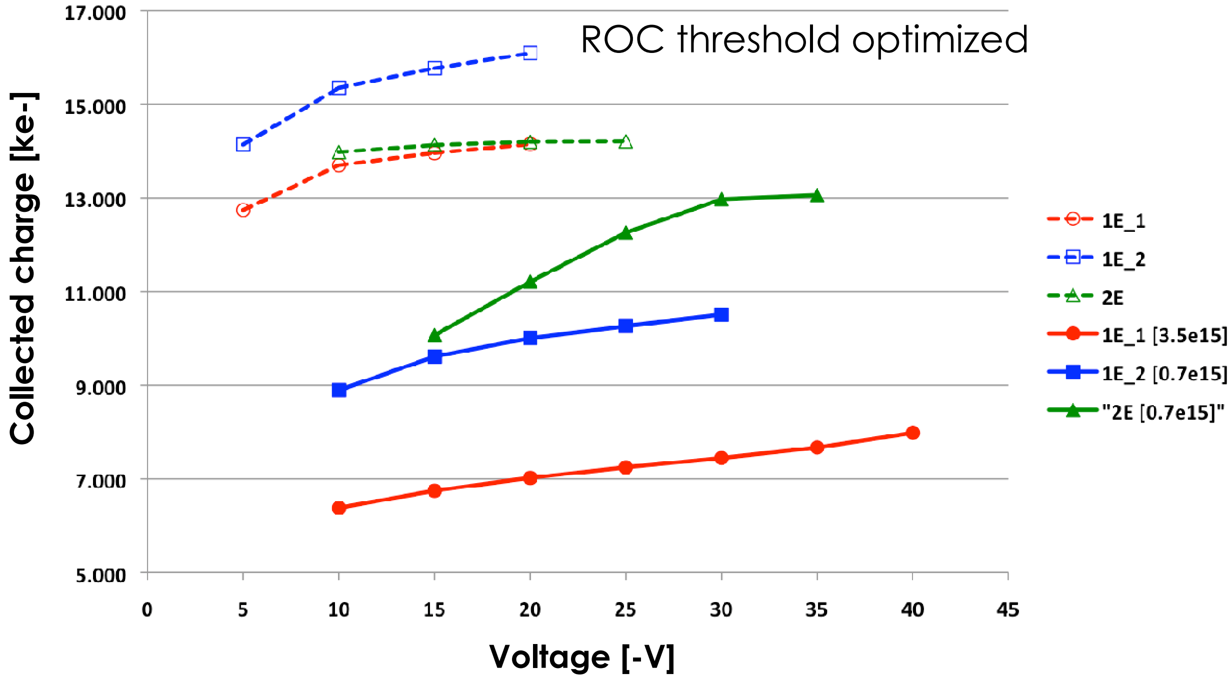
Typical leakage current after irradiation: tens of µA at -20 °C



Effect of irradiation on noise

Noise increases after irradiation even if a direct comparison with pre-irradiation values is difficult because measurements were performed at different temperatures.

POST-IRRADIATION TEST BEAM PRELIMINARY RESULTS: COLLECTED CHARGE AND EFFICIENCY



Efficiency at maximum applied voltage

Sensor	ε [before irradiation]	ε [after irradiation]	Fluence [n_{eq}/cm^2]
1E_1	97.7	37.9	$3.5 \cdot 10^{15}$
1E_2	81.1	59.2	$0.7 \cdot 10^{15}$
2E	97.1	91.1	$0.7 \cdot 10^{15}$

Effect of irradiation on charge collection

All sensors show lower collected charge after irradiation. The effect is more evident in 1E sensors due to greater electrodes distance (and consequent higher trapping probability).

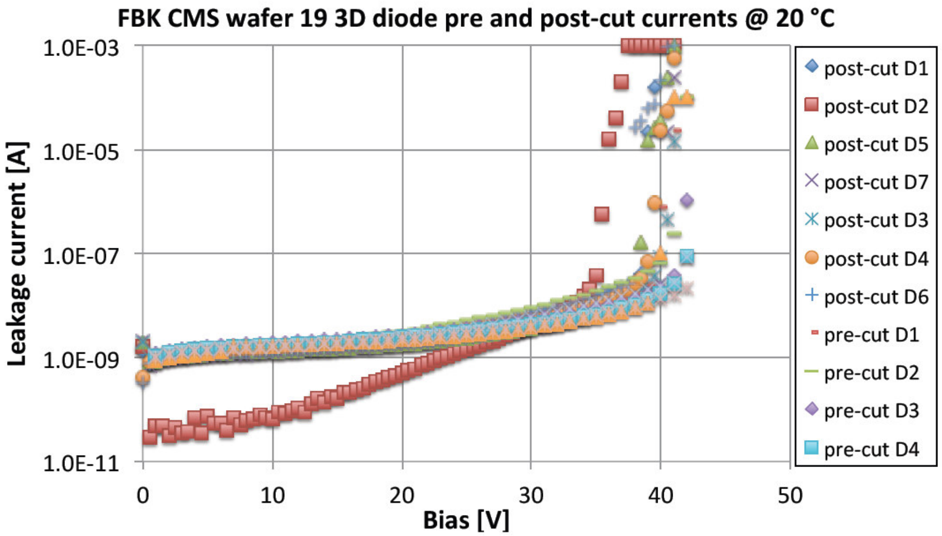
Signal loss @ maximum applied voltage:

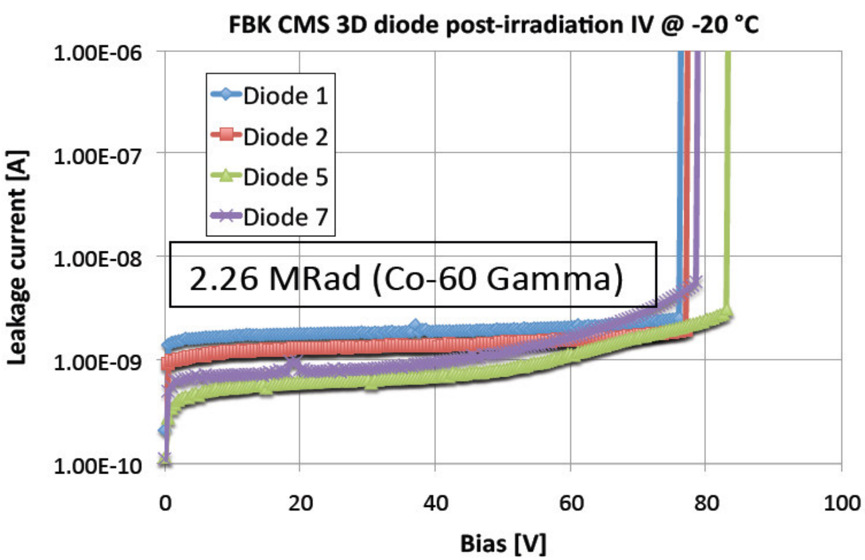
1E: 35% after $0.7 \cdot 10^{15}$ n_{eq}/cm^2
43% after $3.5 \cdot 10^{15}$ n_{eq}/cm^2
2E: 8% after $0.7 \cdot 10^{15}$ n_{eq}/cm^2

Effect of irradiation on track efficiency

Track efficiency decreases after irradiation. 1E sensors more affected.

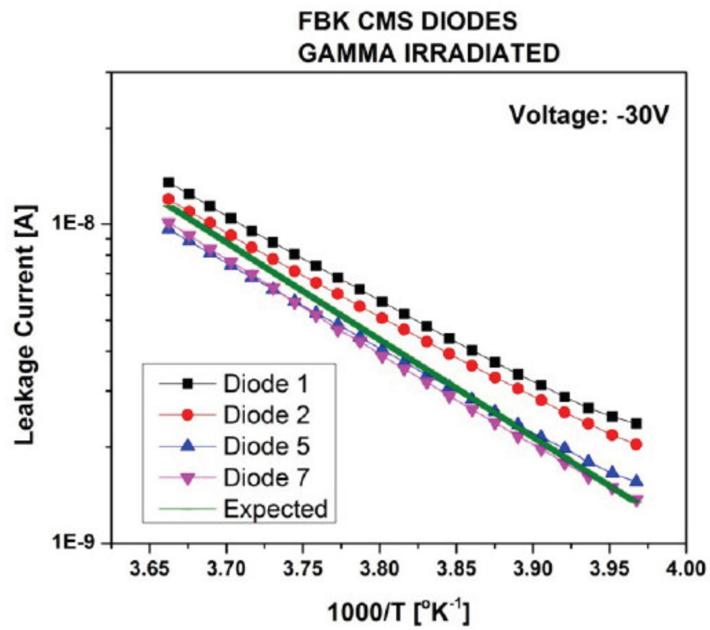
ATLAS10 DIODES: LEAKAGE CURRENT





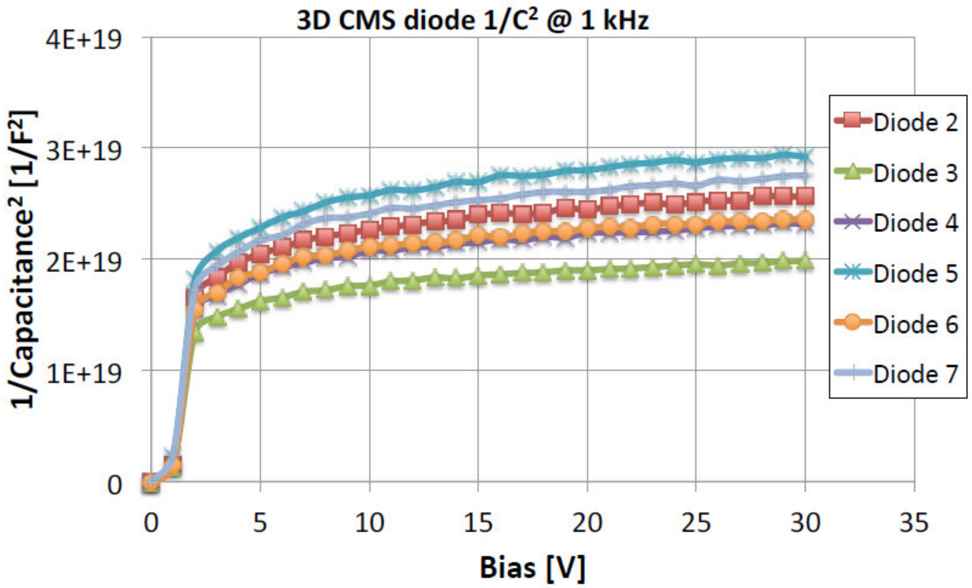
- Diodes irradiated while actively biased (-10 V)
- Breakdown voltage from -40 V to -80 V

Temperature range (0, -20) °C

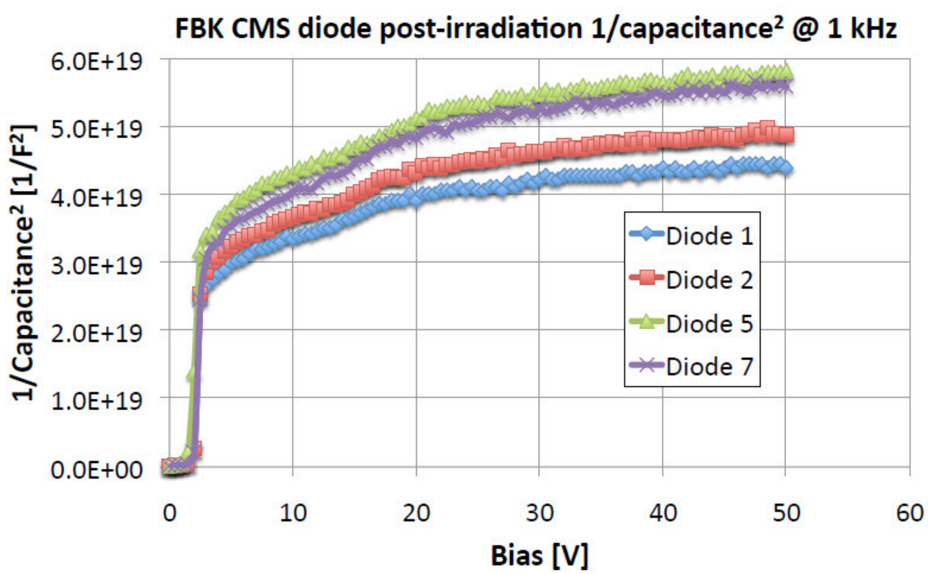


Leakage current behaviour vs temperature as expected

ATLAS10 DIODES: CAPACITANCE



- Pre-irradiation full depletion ~ -7 V at 20 °C
- ~ 200 pF at -10 V



2.26 MRad Gamma
(Co-60 irradiation in Purdue)

- Post-irradiation full depletion ~ -20 V at -20 °C
- ~ 150 pF at -30 V

SUMMARY

- Results for FBK 3D pixel sensors compatible with the CMS readout chip with different electrodes configurations (1E, 2E, 4E) were presented. Sensors belonging to different production batches were tested in Torino, Purdue and FNAL laboratories. A few sensors were irradiated at LANSCE. Tests with beam were performed at FNAL before and after irradiation.

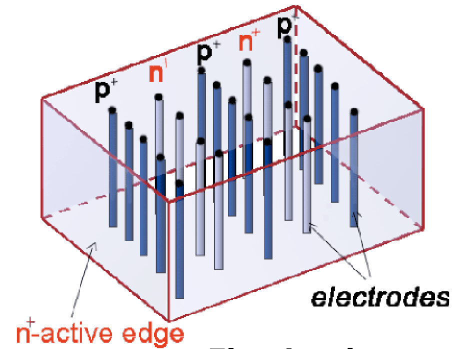
- Preliminary results seems to indicate that 2E sensors are the best compromise in term of radiation hardness and compatibility with the existing CMS ROC (optimized for planar sensors). The data analysis is still ongoing. More sensors were sent for irradiation.

- Latest FBK production looks better in terms of electrical characteristics (lower noise and higher breakdown voltage).

Backup slides

3D SENSORS

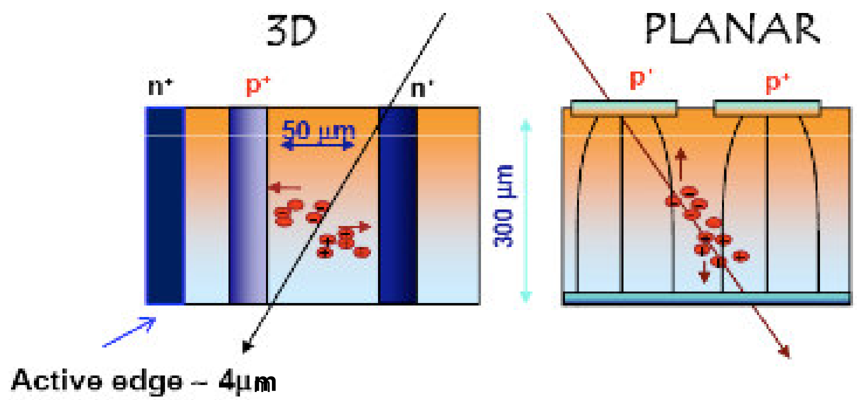
3D sensors consist of an array of columnar electrodes [r ~ 5µm] of both doping types which penetrate in the silicon substrate perpendicularly to the surface.



Electrodes are processed inside the detector bulk instead of being implanted on the wafer's surface.

3D features:

- Electrode distance and active substrate thickness decoupled:
  - low depletion voltage
  - fast collection time
  - small trapping probability after irradiation (**high radiation hardness)**
- Allow implementation of the "Active Edge concept" (dead area reduced up to a few µm from the edge)



- Spatial angular resolution comparable with planar detectors

3D disadvantages:

- Complicated technology (but OK for IBL …..)
- Higher capacitance with respect to planar