Testbeam and laboratory test results of irradiated 3D CMS pixel detectors

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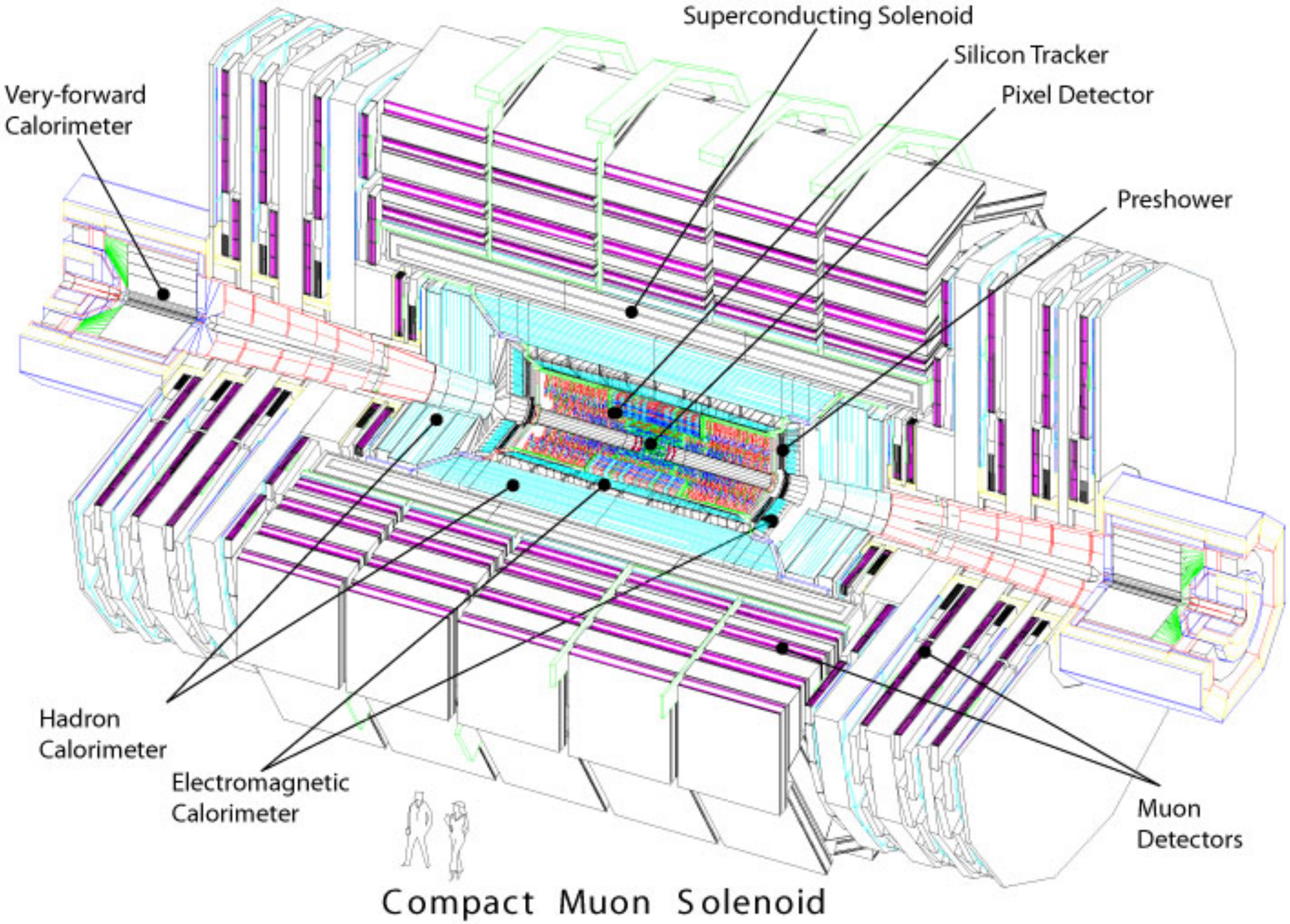
Outline

- The CMS experiment
- The CMS pixel detector
- 3D vs planar technology
- 3D detectors @ CERN LHC
- CMS 3D sensors
- Pre-irradiation
  - laboratory tests
  - beam test results
- Irradiation
- Post-irradiation
  - laboratory results
  - beam test results
- New improved 3D sensors
- Summary & outlook

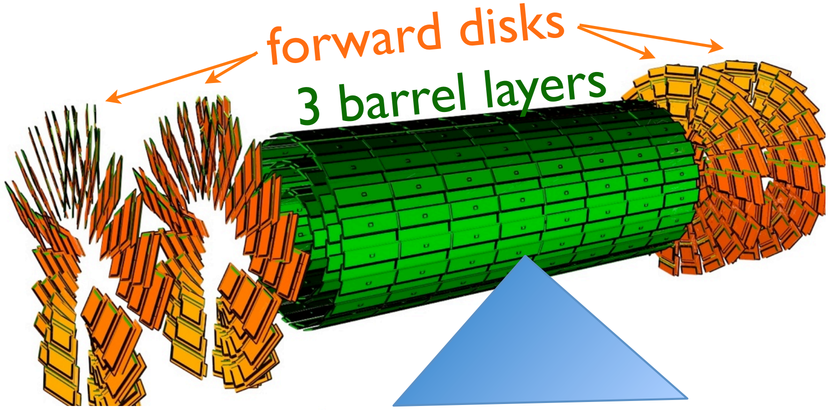
The CMS experiment



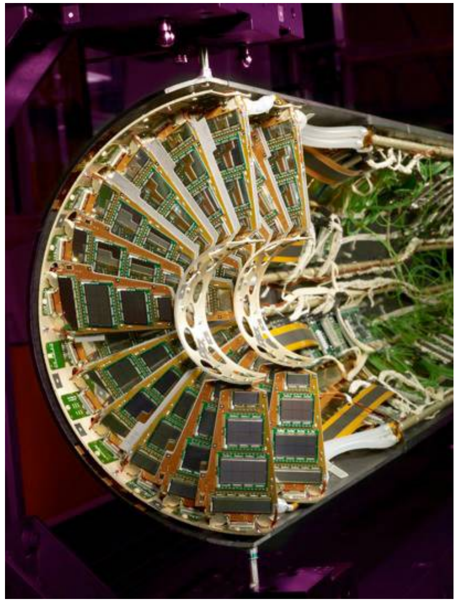
- magnetic field
  4T (in solenoid)
  2T (in muon detector)

- 12.5 kton weight
- 21.6 m height
- 15 m diameter

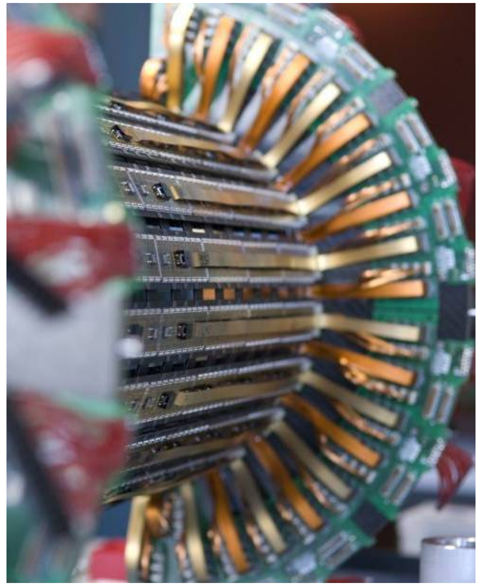
The CMS Pixel Detector

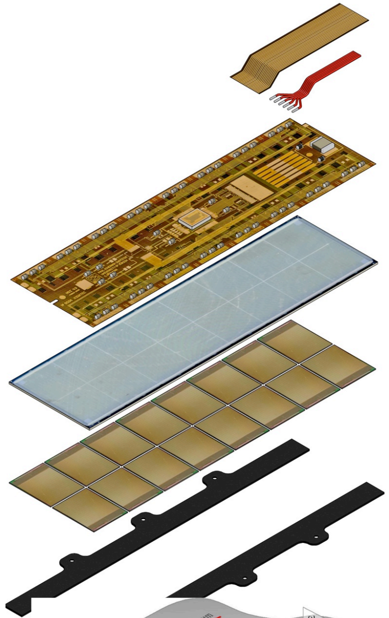


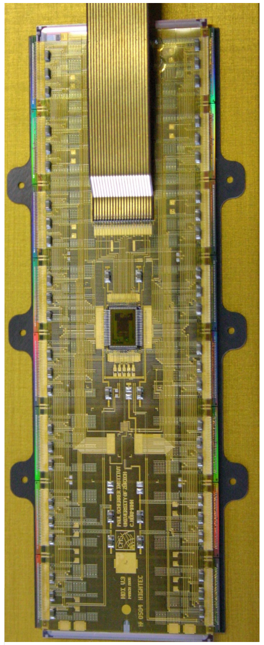
Forward Pixel

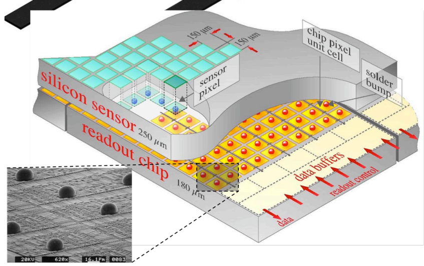


Barrel Pixel





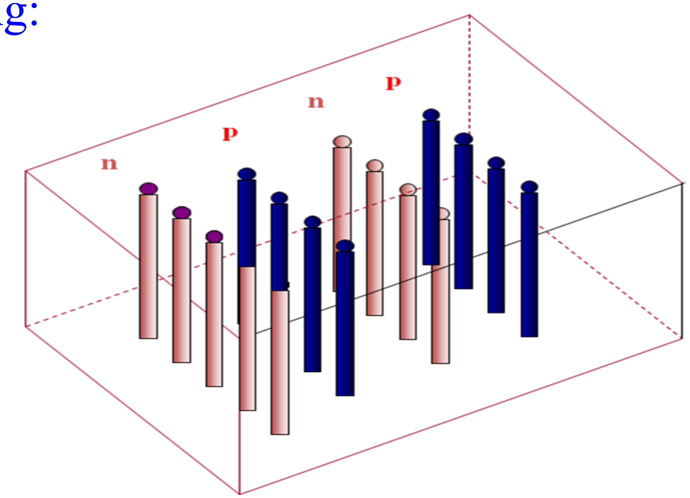




- Barrel layers at r of 4.3,7.3,10.4 cm
- Forward disks at z of ±34.5, ±46.5 cm (modules tilted 20° for better resolution)
- High granularity: 66 MPix camera
  - 100 μm x 150 μm pixel dimensions
- Low mass occupancy
- 1 m^2 silicon coverage

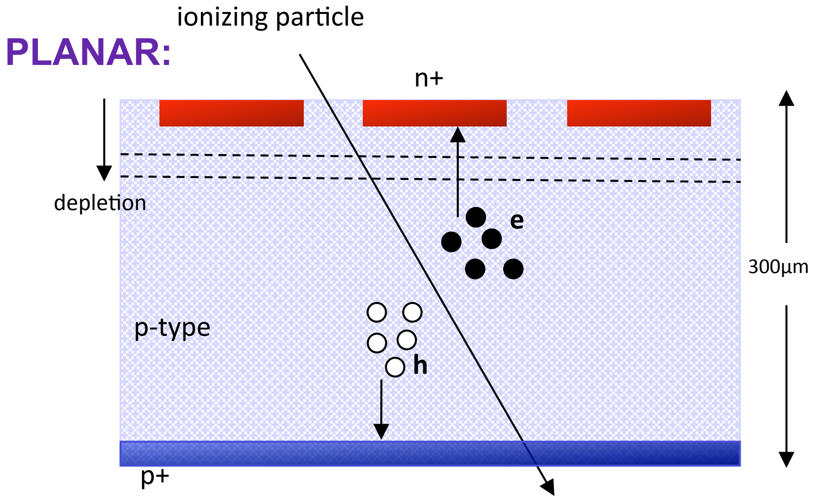
3D vs planar technology

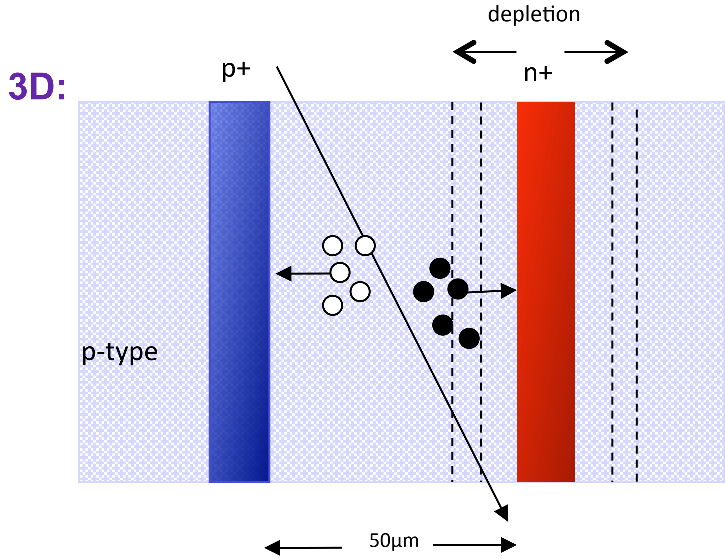
- p+ and n+ electrodes are arrays of columns that penetrate into the bulk
- Lateral depletion and charge collection is sideways
- Superior radiation hardness due to smaller electrode spacing:
  - smaller carrier drift distance
  - faster charge collection
  - less carrier trapping
  - lower depletion voltage



Disadvantages:

- Higher noise
- Complex, non-standard processing

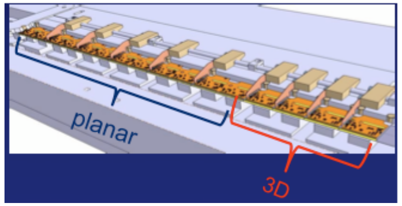


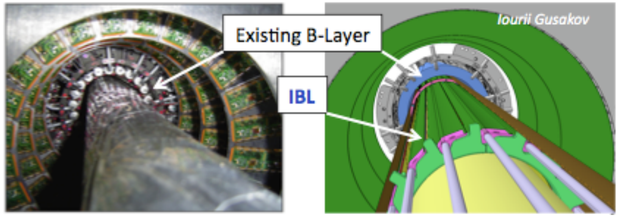


3D @ CERN LHC

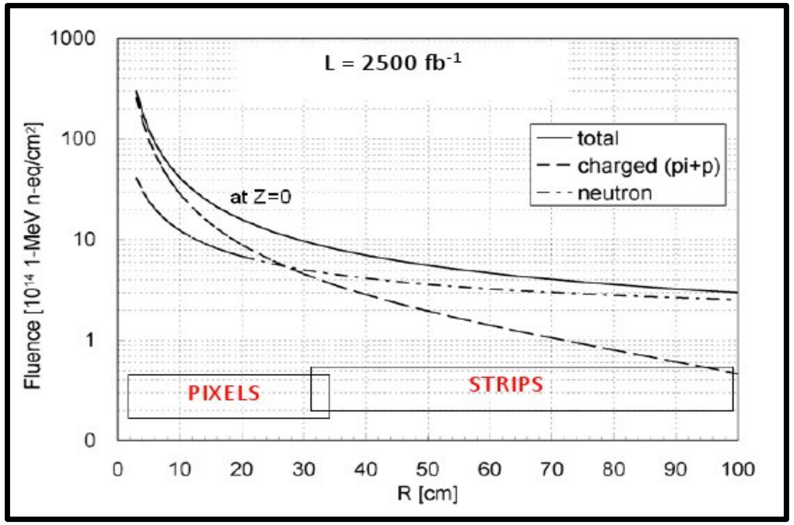
3Ds are promising tracking detector candidates for future upgrades at LHC

25% of ATLAS IBL will be 3D sensors at phase I upgrade in 2015



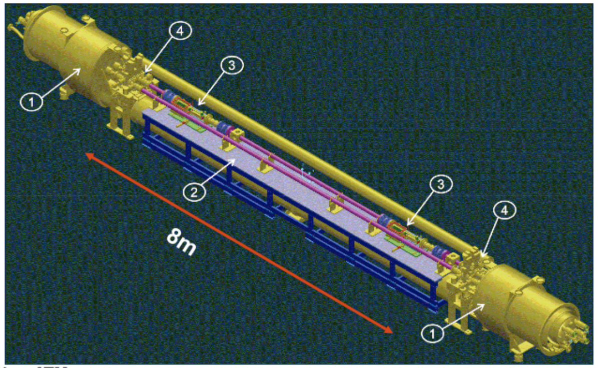


- **New rad-hard sensor candidates for the HL-LHC CMS vertex detector (L = $10^{35}cm^{-2}s^{-1}$)**
- Equivalent dose ~ $10^{16}n_{eq}/cm^2$ @ r = 5 cm
- Current CMS pixel detector can collect 50% charge at the fluence of ~ $1x10^{15}n_{eq}/cm^2$ at >= 600V (doi:10.1016/j.nima.2010.03.157)



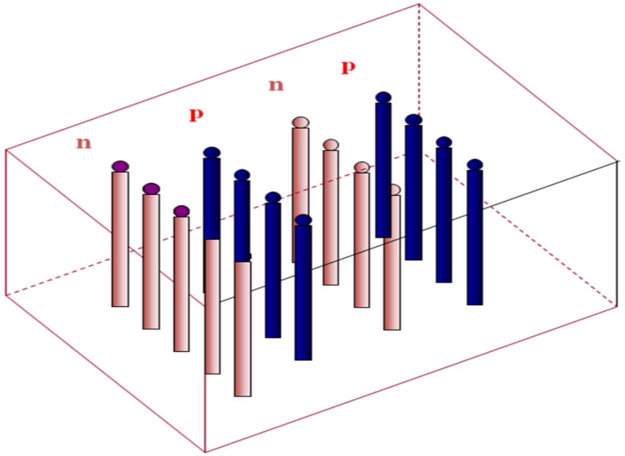
- **HPS (near beam proton spectrometer - under approval for CMS)**

Crucial requirement for this application: radiation hardness and active edges



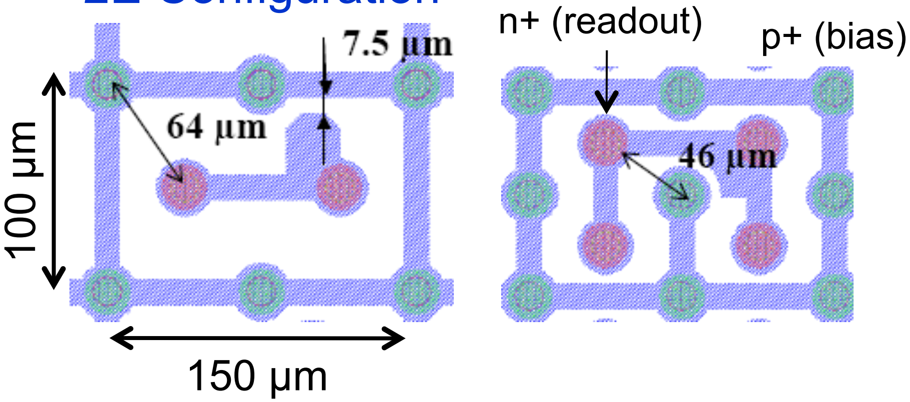
3D layouts (200 µm substrate thickness)

SINTEF 3D



2E Configuration

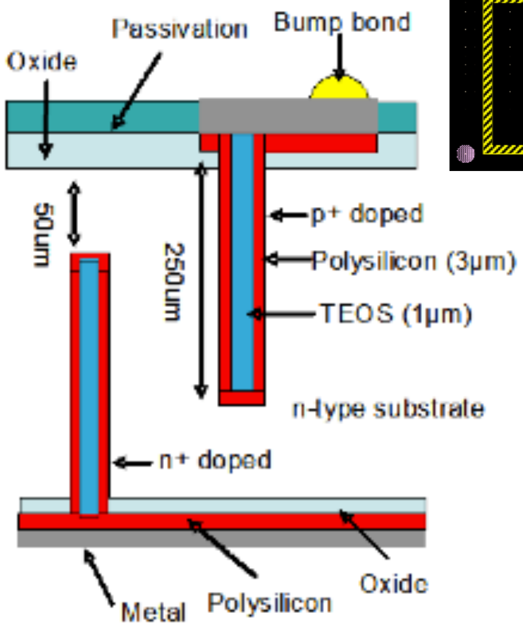
4E Configuration

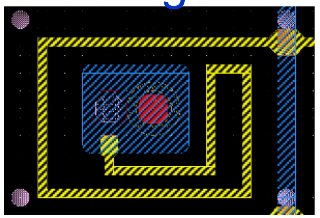


Single-side etching

CNM 3D

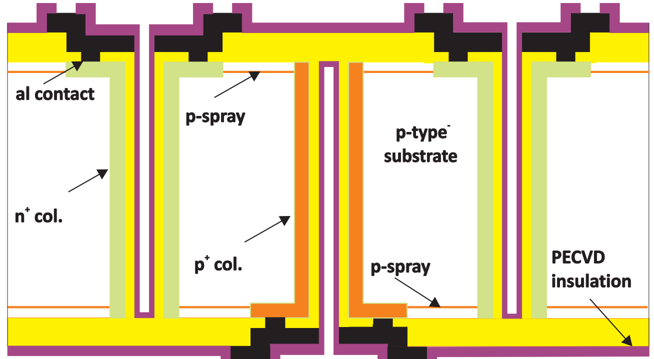
1E Configuration

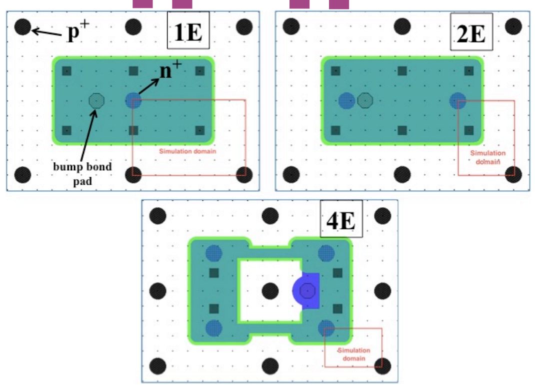




Double-side etching

FBK 3D





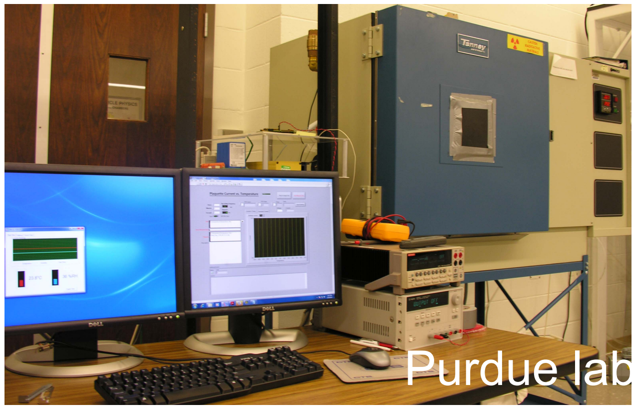
Double-side etching

3D sensor assembly

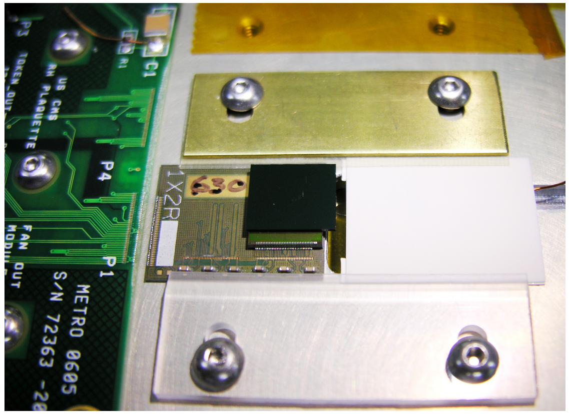
- 3D sensors bump-bonded to CMS PSI46v2 readout chip
  - At IZM for SINTEF 3Ds (PbSn)
  - At SELEX for FBK 3Ds (In)
  - At IZM for CNM 3Ds (PbSn)
- CMS sensor dimensions 52(col)x80(row) (100 μm x 150 μm)
- Wire bonding and assembly done at Purdue, FNAL, and Torino
- *Purdue flip-chip bonder* fully functional for next 3D sensors

<u>Lab testing</u>:

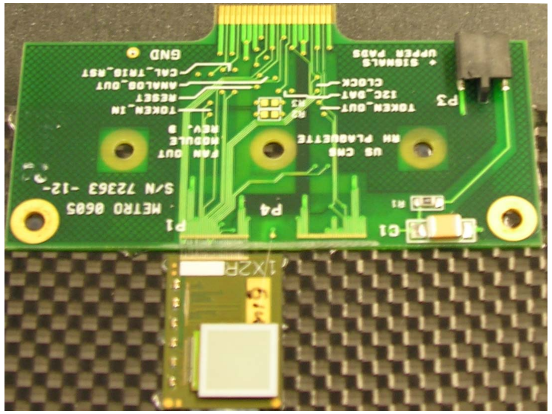
- ROC calibration
- Leakage current
- Noise
- Radioactive source testing

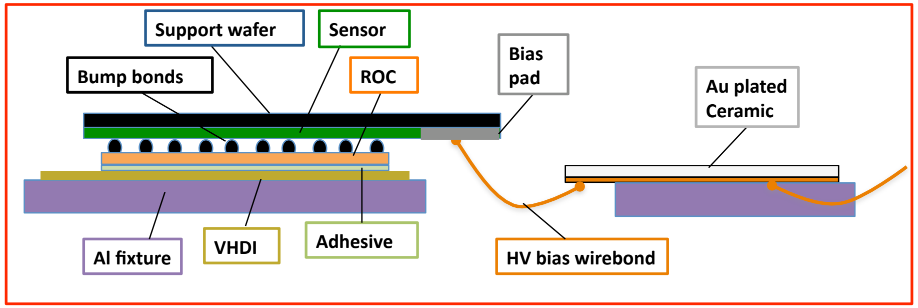


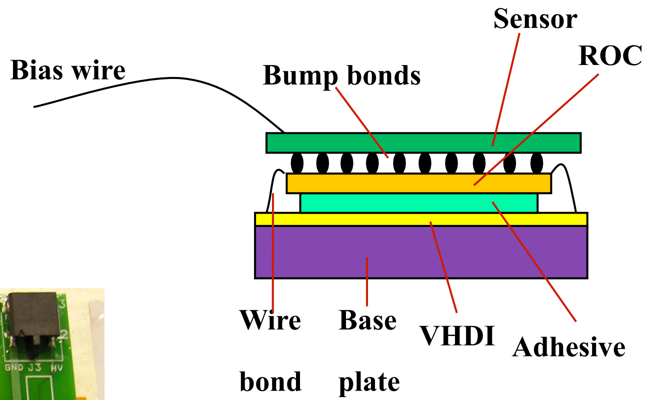
CMS 3D sensor assembly



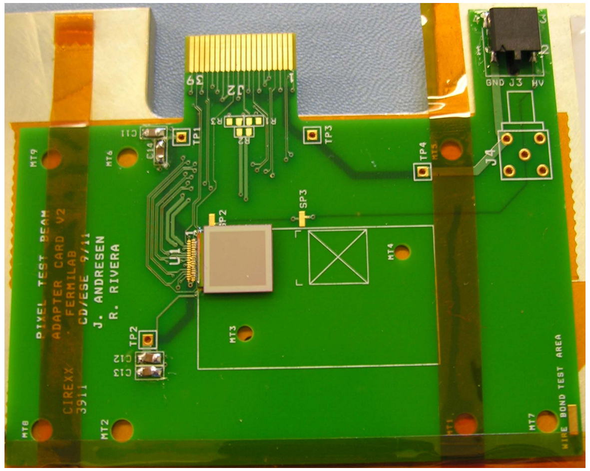
Plaquette assembly





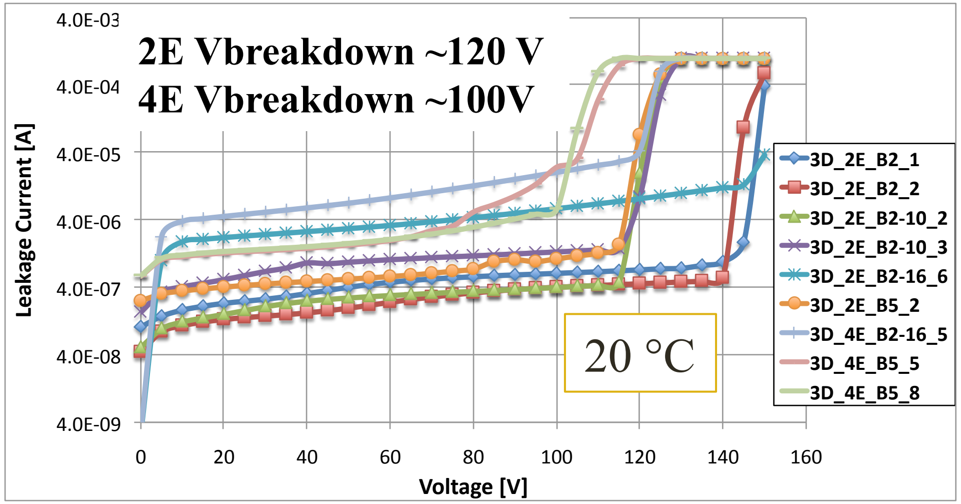


Testboard assembly

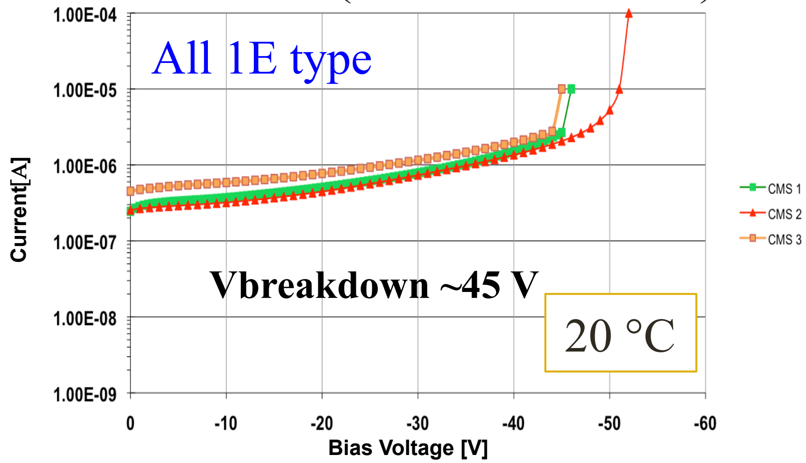


Leakage current measurements

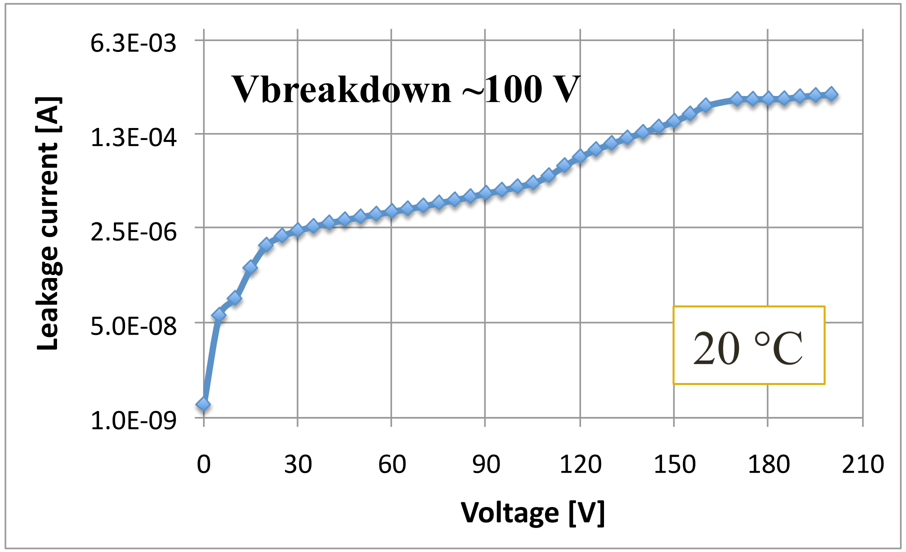
SINTEF 3D



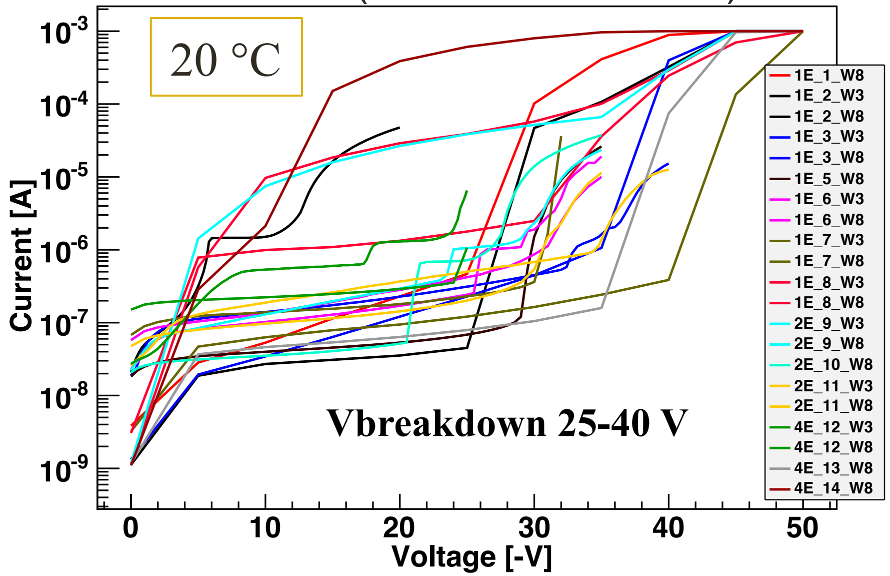
FBK 3D (ATLAS09 batch)



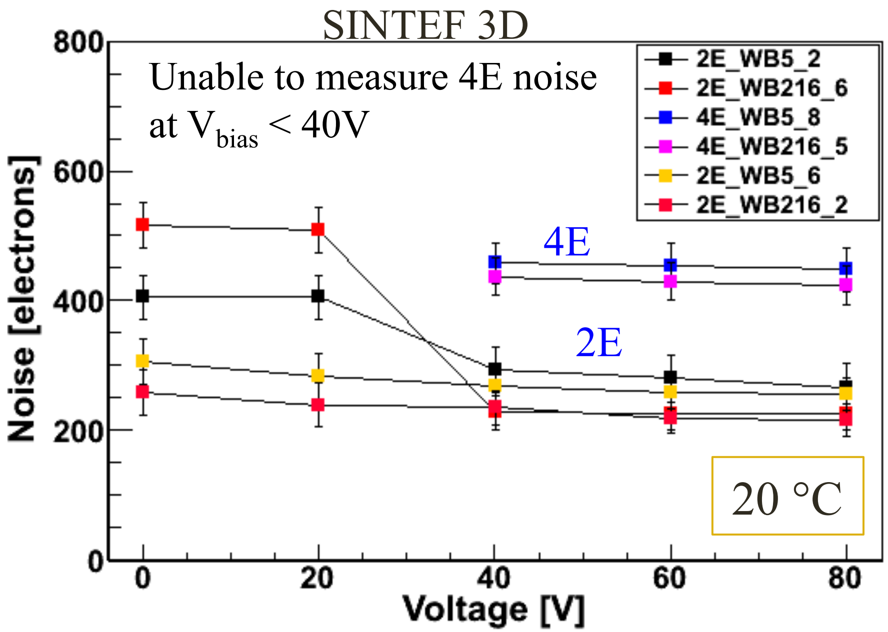
CNM 3D

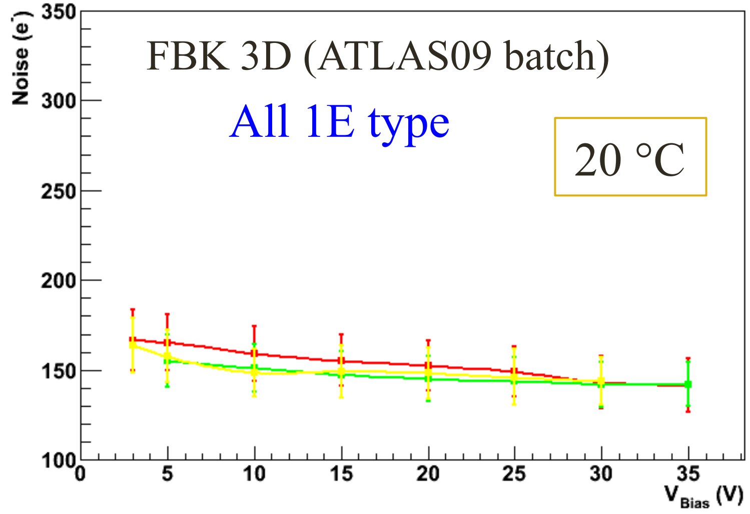


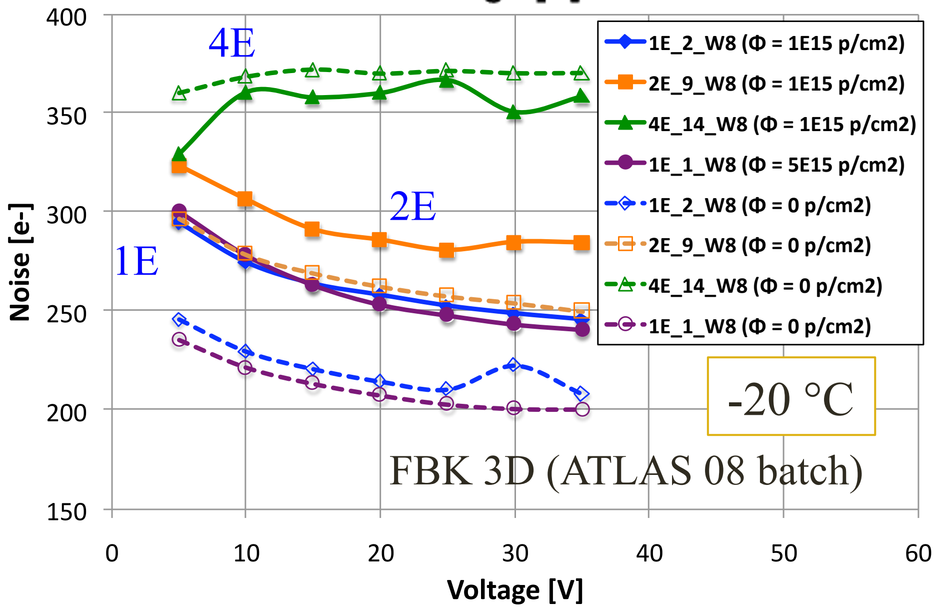
FBK 3D (ATLAS08 batch)

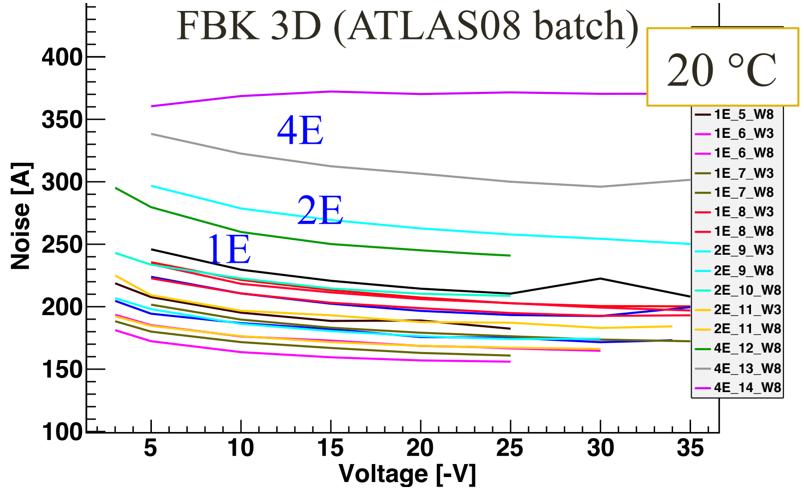


Noise measurements







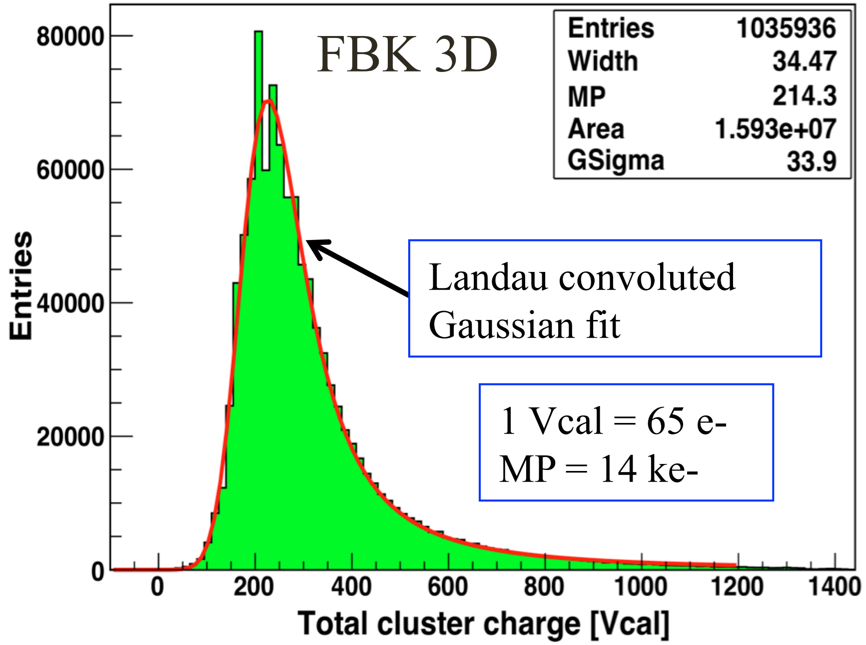


- Higher number of electrodes, larger capacitance → larger noise
- CMS planar sensor noise 100-150 electrons

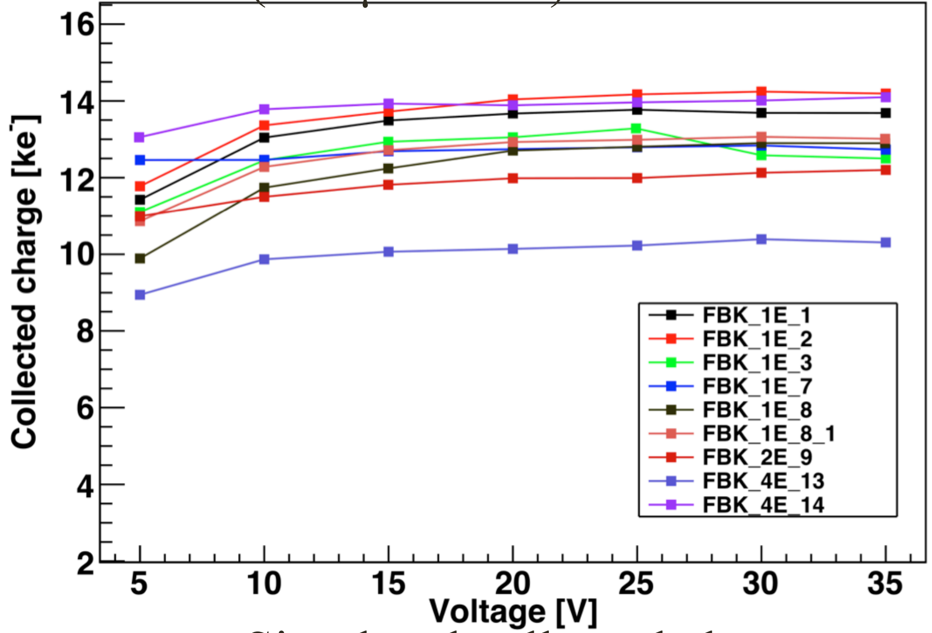
Source charge collection

PURDUE UNIVERSITY

- Sr-90 source: 1 mCi, $E_{\beta} = 0.546$ MeV
- Random trigger used



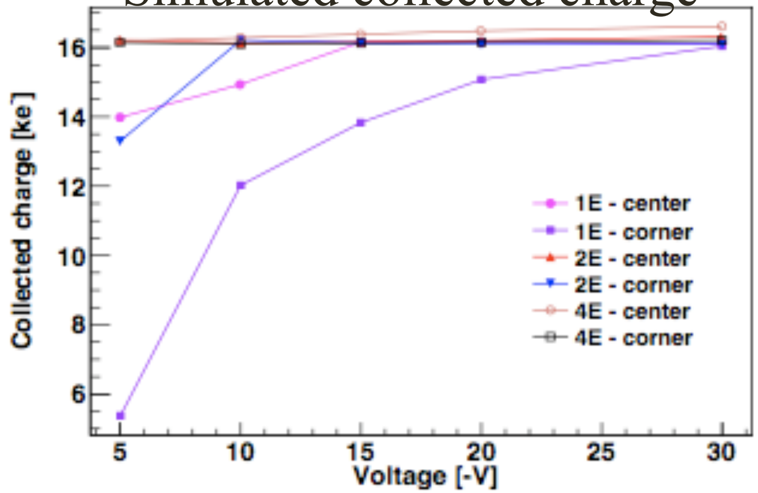
FBK-ATLAS08 batch (200 µm thick)



Slight difference between measured and simulated collected charges:

- combined effect of charge sharing and readout chip threshold (~3.9 ke-)
- Lower chip gain calibration due to high noise of 3D sensors
- wafer thickness uncertainty (200±20) µm

Simulated collected charge



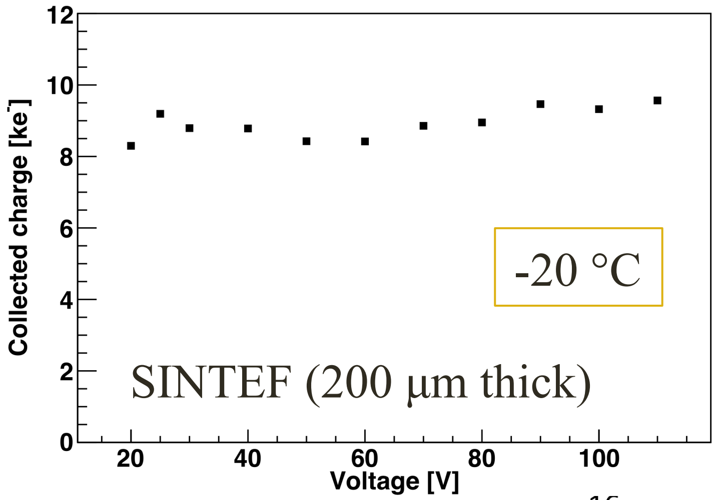
Irradiation

- Irradiation at the Los Alamos Neutron Science Center (LANSCE) with 800 MeV protons/cm^2
  - Fluences: 5E14, 1E15, and 5E15 p/cm^2 (FBK)
  - Fluences: 1E15, and 5E15 p/cm^2 (SINTEF)
  - Fluences: 1E14, 3E14, 5E14, and 1E15 p/cm^2 (CNM)
- Post-irradiation lab (@ Purdue) and beam tests (@ FNAL) performed for SINTEF and FBK 3D sensors
  - CNM sensors only tested in testbeams
- Most of the readout chips work after irradiation
  - Except SINTEF case: 1 out of 6 ROCs worked, and CNM sensors had calibration problems
- Post-irradiation lab measurements carried out in the thermal chamber running at -20 °C
  - sensor temp estimated by an IR camera to be -7 °C

800 MeV proton to 1 MeV neutron equivalent conversion factor is 0.7

Post-irradiation charge collection

- Sr-90 source: 1 mCi, $E_\beta = 0.546$ MeV
- Random trigger used

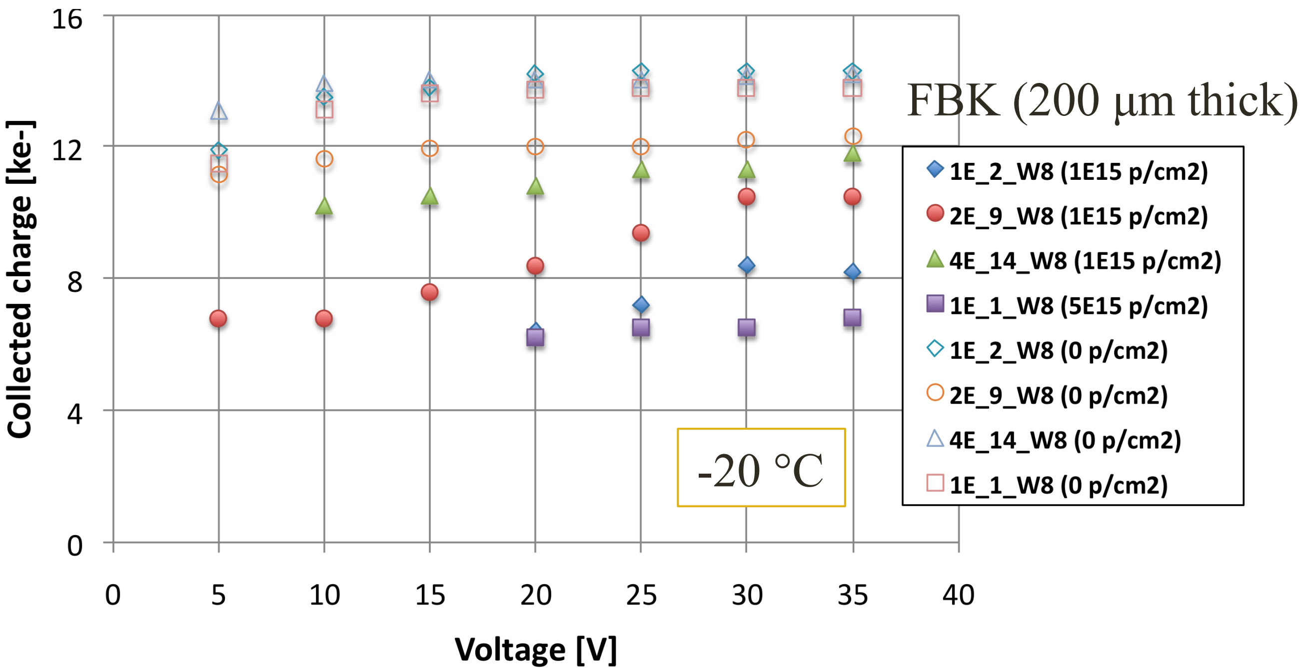


Signal LOSS in FBK 3D (@ -30V, 3900 electrons threshold):

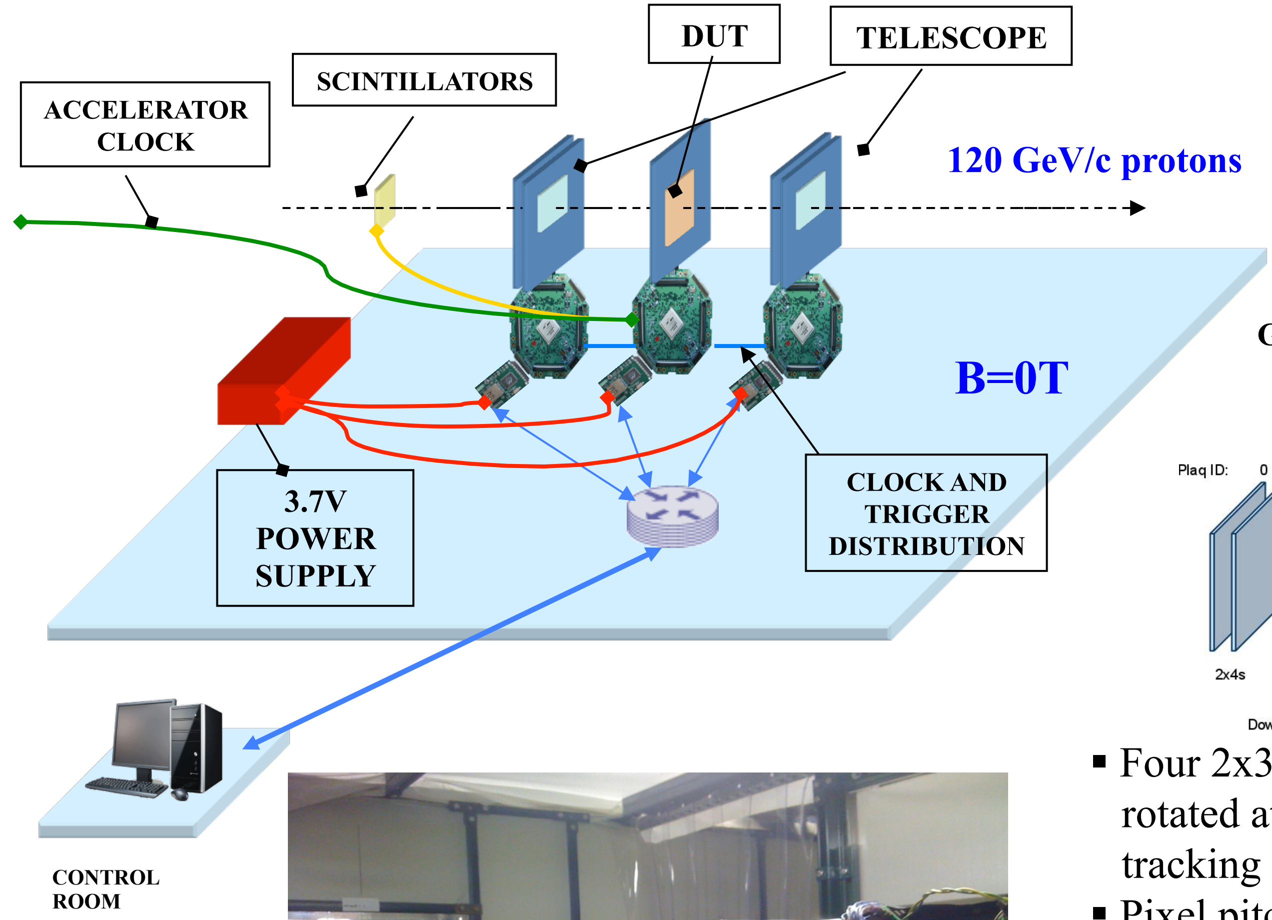
1E 43% after 1E15 p/cm^2 (0.7E15 n_{eq}/cm^2)
1E 50% after 5E15 p/cm^2 (3.5E15 n_{eq}/cm^2)
2E 14% after 1E15 p/cm^2 (0.7E15 n_{eq}/cm^2)
4E 14% after 1E15 p/cm^2 (0.7E15 n_{eq}/cm^2)

CMS pixel 50% after 1E15 n_{eq}/cm^2 at 600V
*(*doi:10.1016/j.nima.2010.03.157*)*

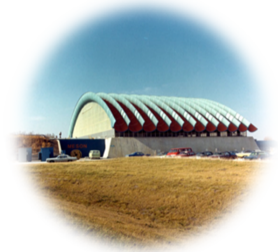
Winner is 2E ➔



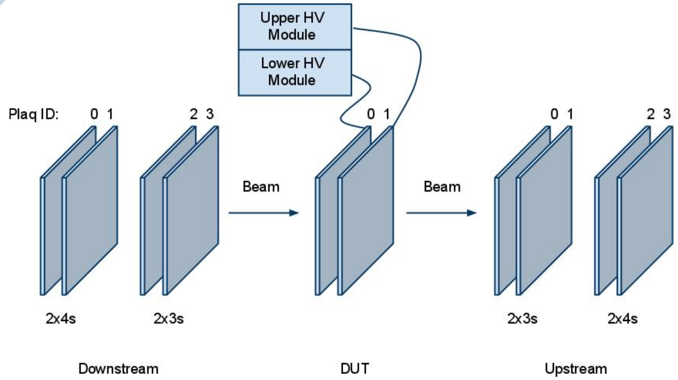
Fermilab testbeam setup

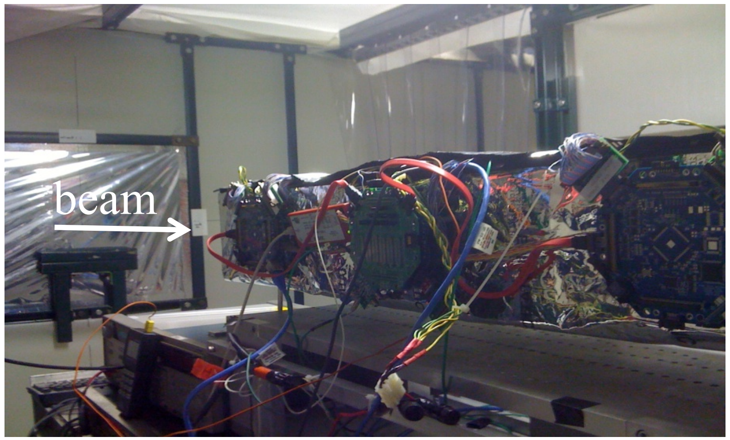


FNAL MESON AREA



Geometrical layout of the telescope



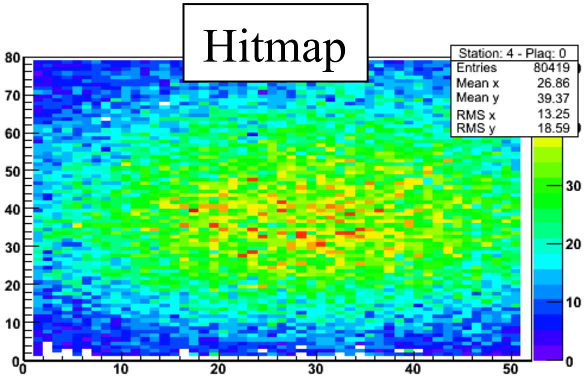


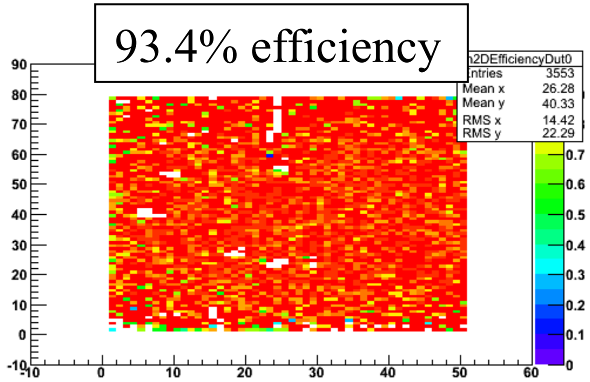
- Four 2x3 and four 2x4 CMS pixel modules rotated at 25° w.r.t. beam to improve tracking resolution
- Pixel pitch: 100 μm along the rotated axis (150 μm in the other direction)
- Alignment done with a software developed at Milano Bicocca
- Telescope resolution on DUT: 6 μm

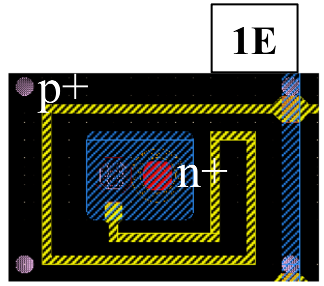
Beam test: pre-irradiation

CNM 3D, 1E

V_{bias} = -15V : 20° tilt



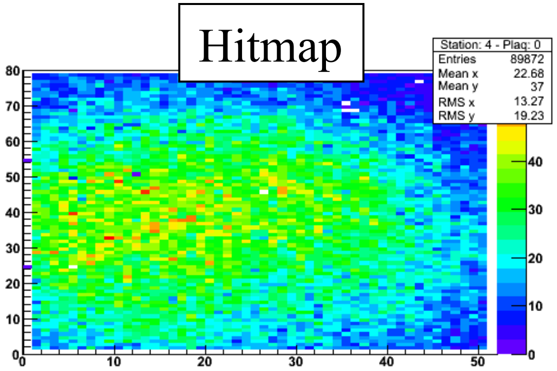


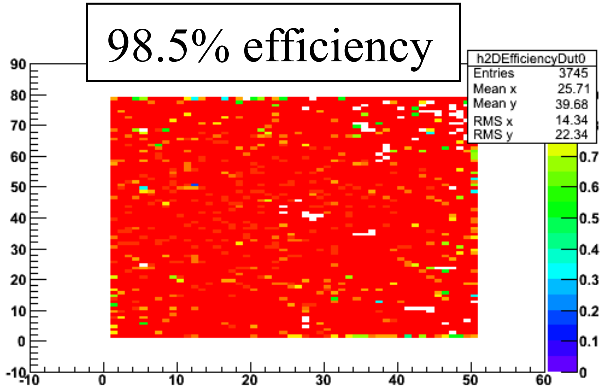


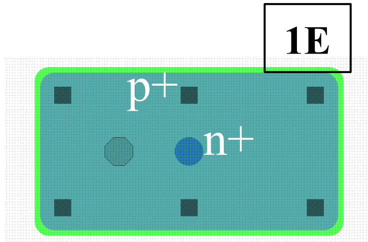
FBK 3D, 1E

V_{bias} = -15V : 20° tilt

ATLAS08 batch



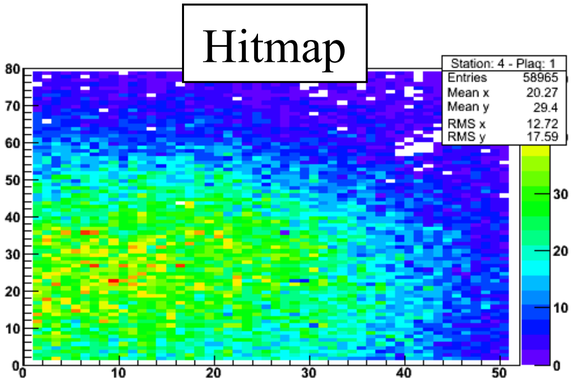


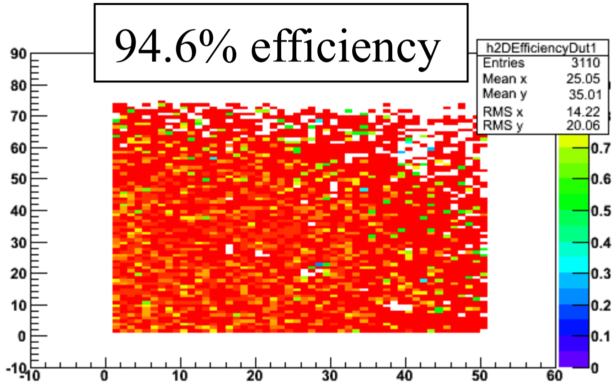


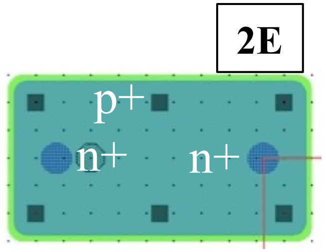
FBK 3D, 2E

V_{bias} = -5V : 20° tilt

ATLAS08 batch



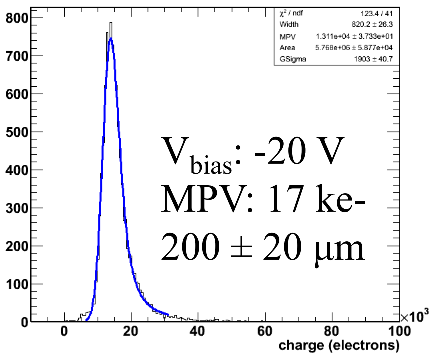




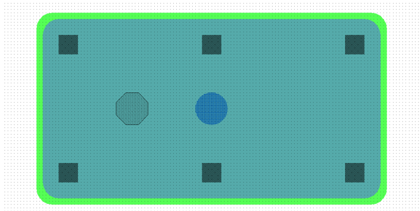
Beam tests: pre-irradiation

FBK (ATLAS09 batch, slim edge), 1E

Charge collection

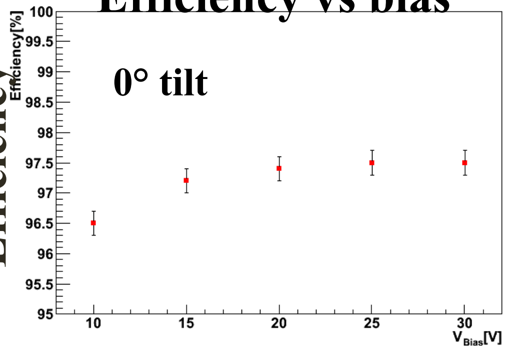


1E configuration

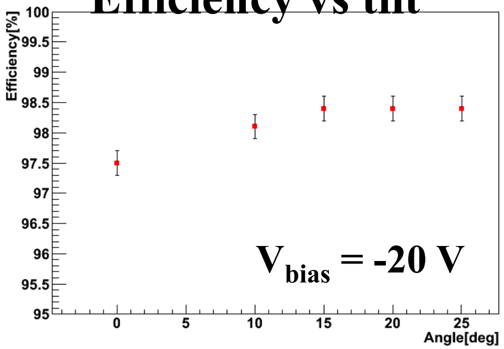


Efficiency

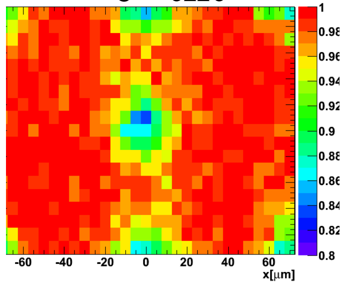
Efficiency vs bias



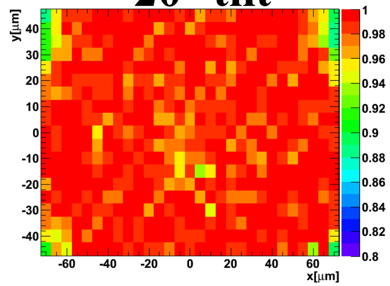
Efficiency vs tilt



0° tilt

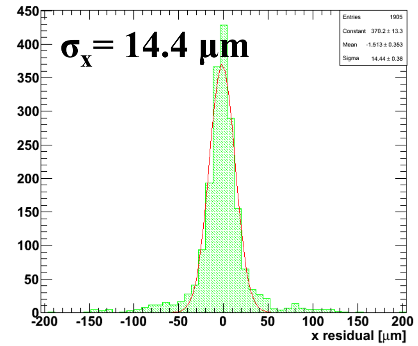


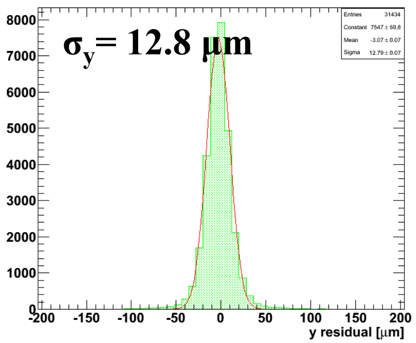
20° tilt



Spatial resolution

Residuals for 2 pixel clusters

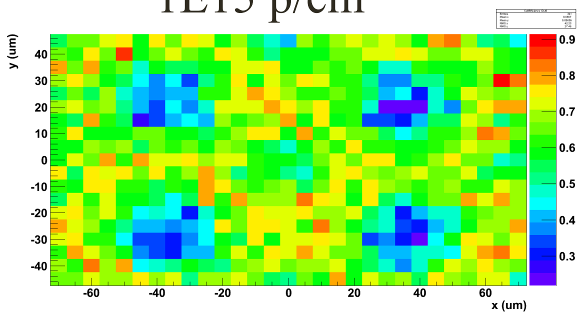


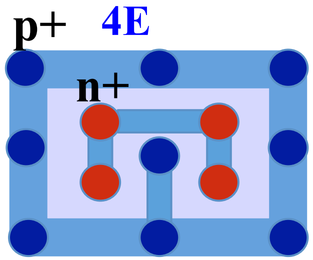


Beam test: post-irradiation

SINTEF (@ -80V)

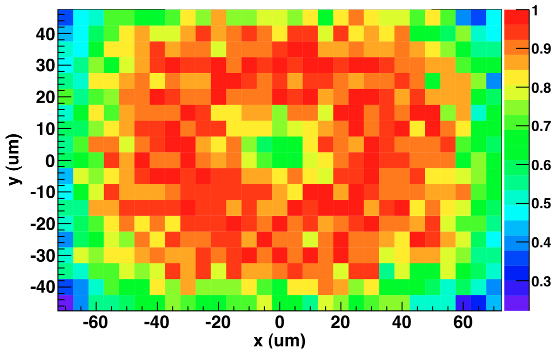
1E15 p/cm^2

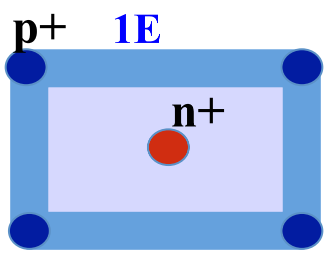




CNM (@ -80V)

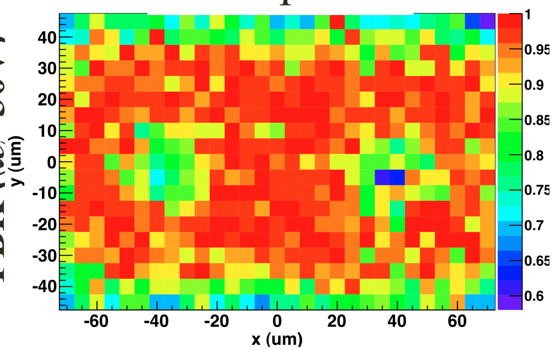
3E14 p/cm^2

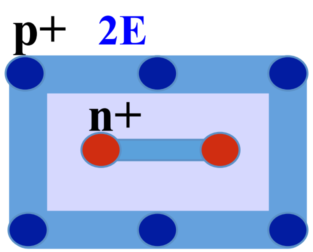




FBK (@ -30V)

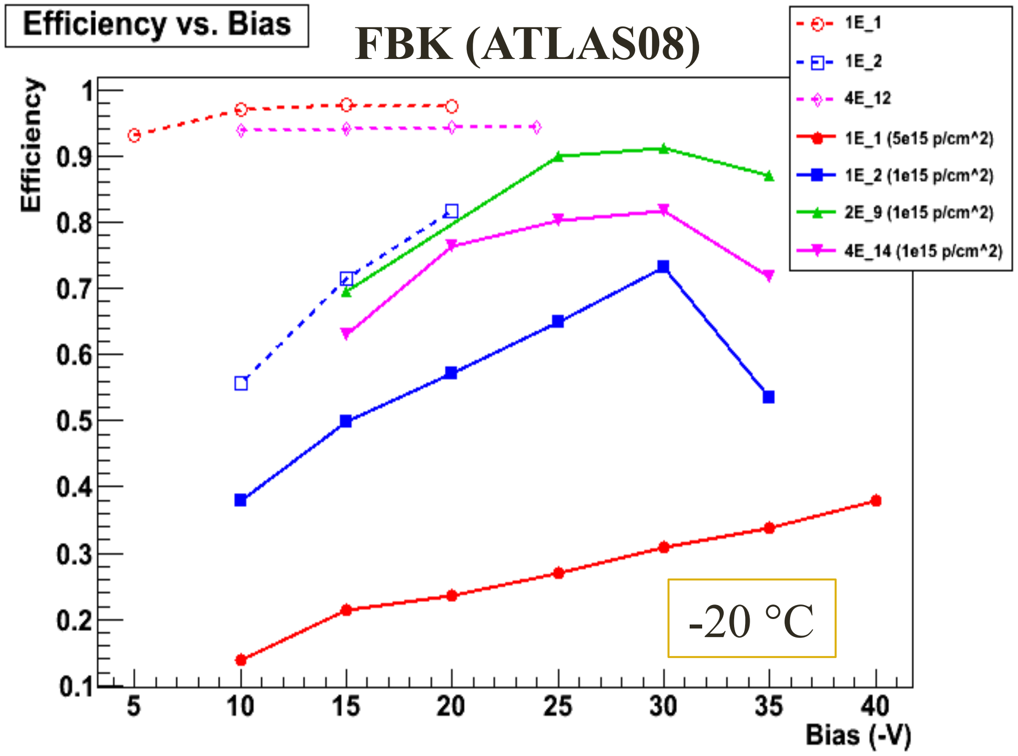
1E15 p/cm^2





- Measured at -20 °C
- No tilt (0° degree) wrt beam
- Electrodes are less sensitive: observed lower efficiency in electrode regions
- Simulations ongoing to understand post-irradiation sensor efficiencies

Beam test: post-irradiation



- Track efficiency decreases after irradiation. 1E sensors more affected
- Efficiency increases with bias, due to larger electric field in the bulk, up to breakdown where it falls off
- Not all sensors tested up to breakdown

Efficiency at maximum bias

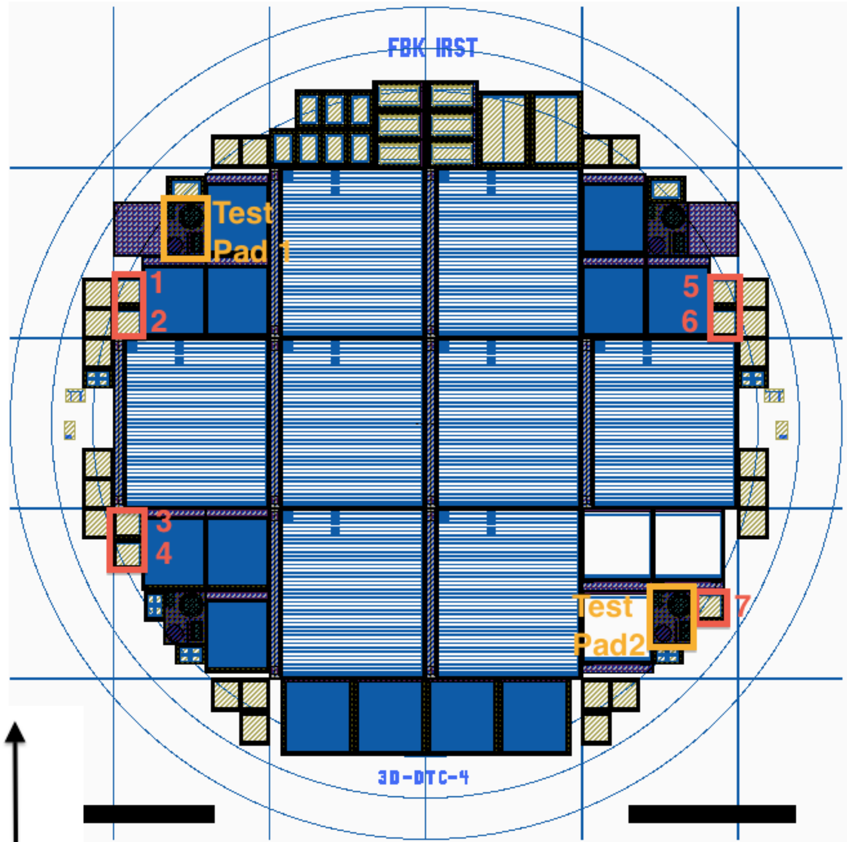
Sensor	Pre-irradiation	Post-irradiation	Fluence [n_{eq}/cm^2]
1E_1	97.7	37.9	$3.5\ 10^{15}$
1E_2	81.1	59.2	$0.7\ 10^{15}$
2E	97.1	91.1	$0.7\ 10^{15}$

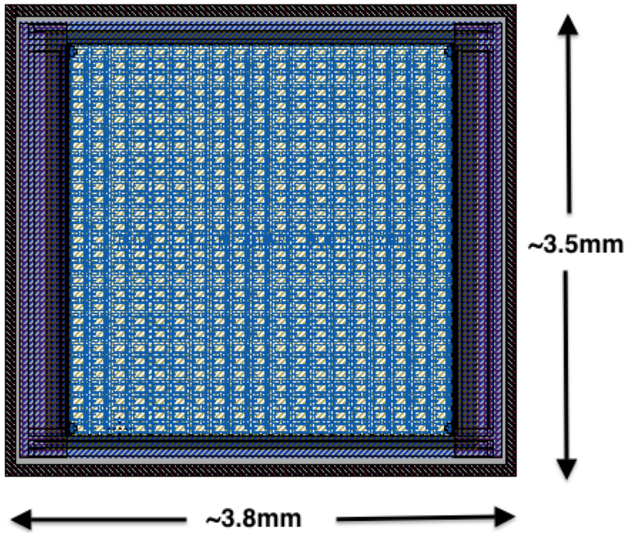
New improved 3D sensors

- **WAFER LAYOUT:**
- ATLAS10 batch
- CMS-1E diode only
- Diodes are highlighted (RED)
- The shipped test structures are also highlighted (ORANGE)

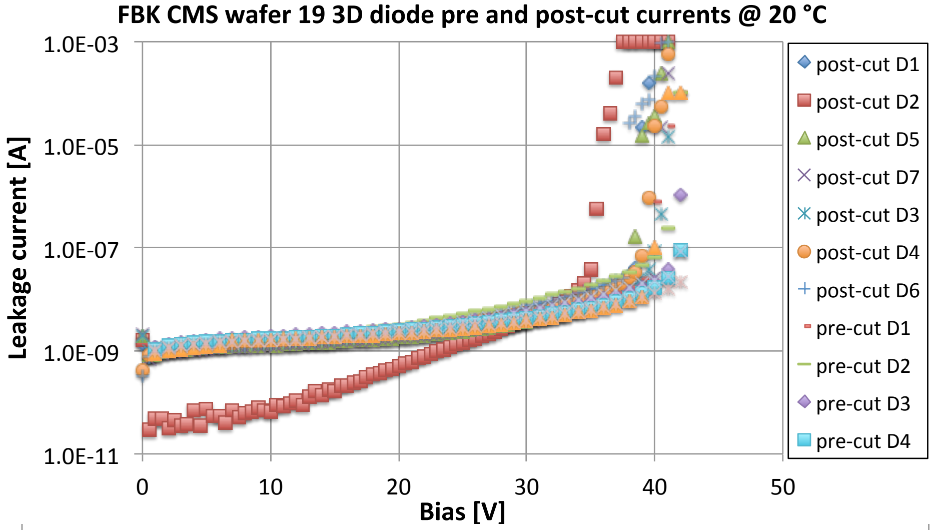
- **Test structures (TestPad):**
  - Gate controlled diode
  - MOS capacitor
  - Planar diode
  - Capacitor

- **CM 1E diodes:**
- 3.5x3.8 mm2
- 200 +- 20 um thickness
- 19x29 pixel arrays

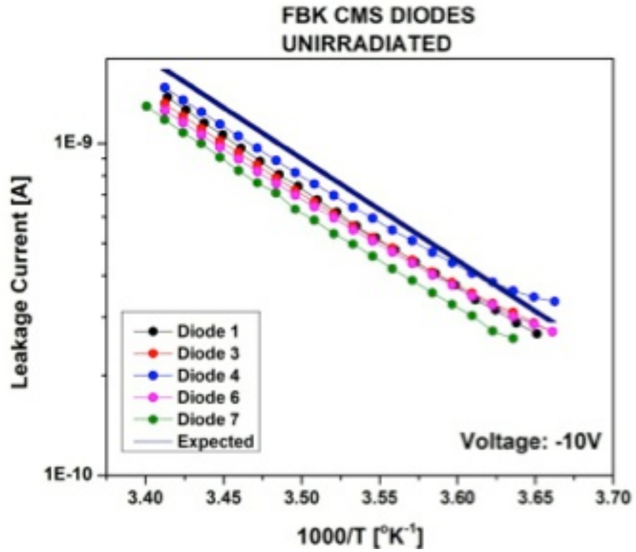


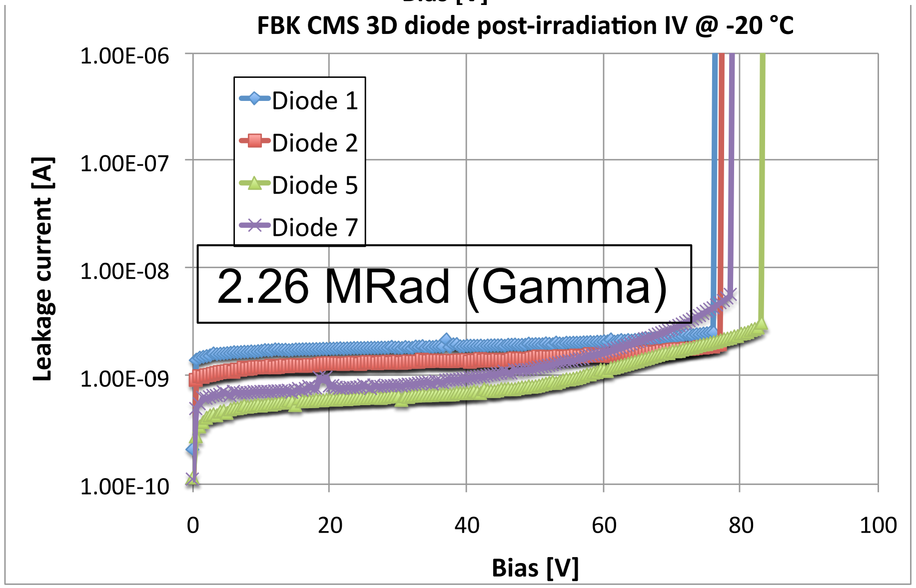


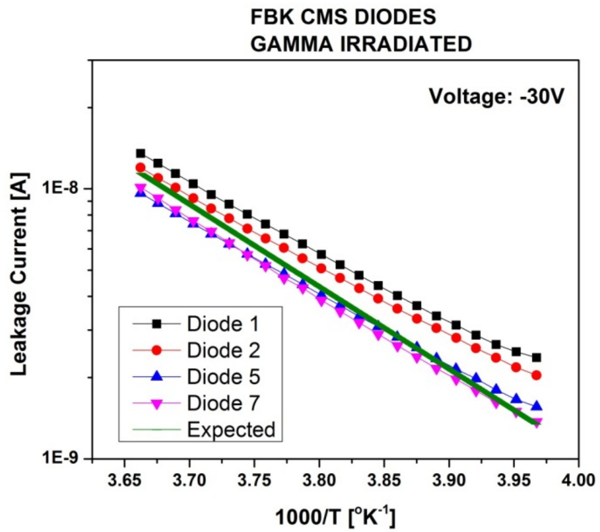
Diodes pre- and post-cut IV measurements



Temperature range: 0 °C- 20 °C

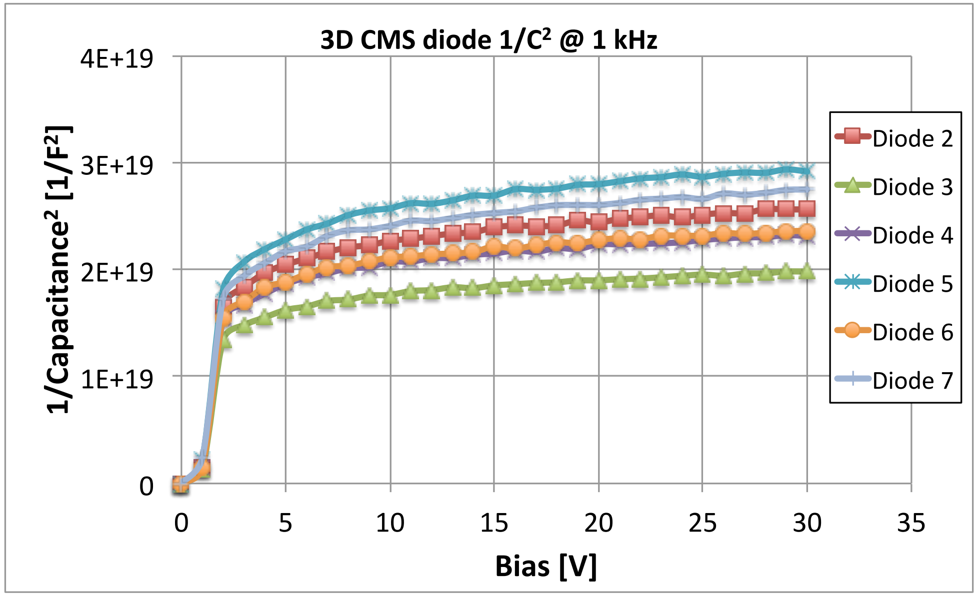




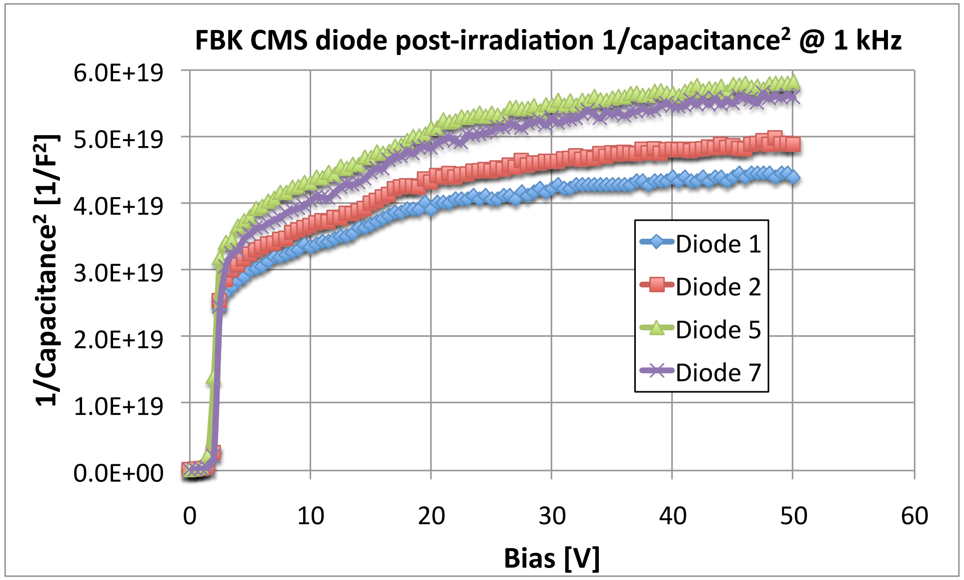


- Diodes irradiated while actively biased (-10V)
- Breakdown improved from -40 V to -80 V

Capacitance measurements



- Full depletion ~ -7 V at 20 °C
- ~200 pF at -10 V



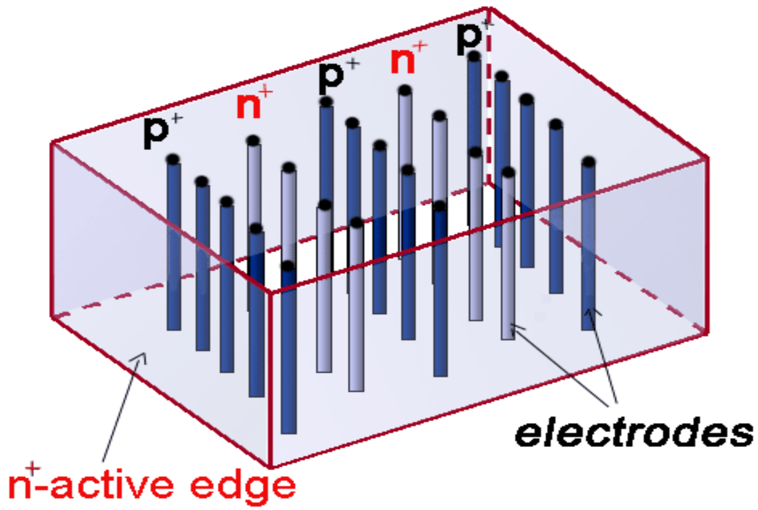
2.26 MRad (Gamma irradiation facility at Purdue)

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

Summary & outlook

- 3D sensors have several features outperform planar sensors
- Sensors received from SINTEF (Norway), FBK (Ital), and CNM (Spain)-
- Breakdown voltage: SINTEF > 100V, CNM > 100V, and FBK <= 40V
- 3D sensors have higher noises
- Pre-irradiation beam test results show efficiencies higher than 90%
- Irradiated fluences are between 1E14 and 3.5×10^{15} n_{eq}/cm^2 (800 MeV protons)
- Beam tests at Fermilab
  - > 90% tracking efficiency before irradiation
  - Low tracking efficiency after irradiation due
    - High readout threshold
    - Low electric field (lower post-irradiation breakdown voltage)
  - Good charge collection after heavy irradiation wrt planar
  - 2E configuration outperforms 1E and 4E after irradiation
- Expecting more 3Ds from SINTEF, FBK and CNM
- Ongoing simulation to develop understanding FBK beam test results
- New irradiation fluences up to 1E16 n_{eq}/cm^2

CMS 3D collaboration



3DC

Czech Technical University, Fermilab, Purdue University, INFN Torino, SINTEF, SLAC, University of Hawaii, University of Manchester