Double-Sided 3D Silicon Strip Detectors for the High-Luminosity LHC

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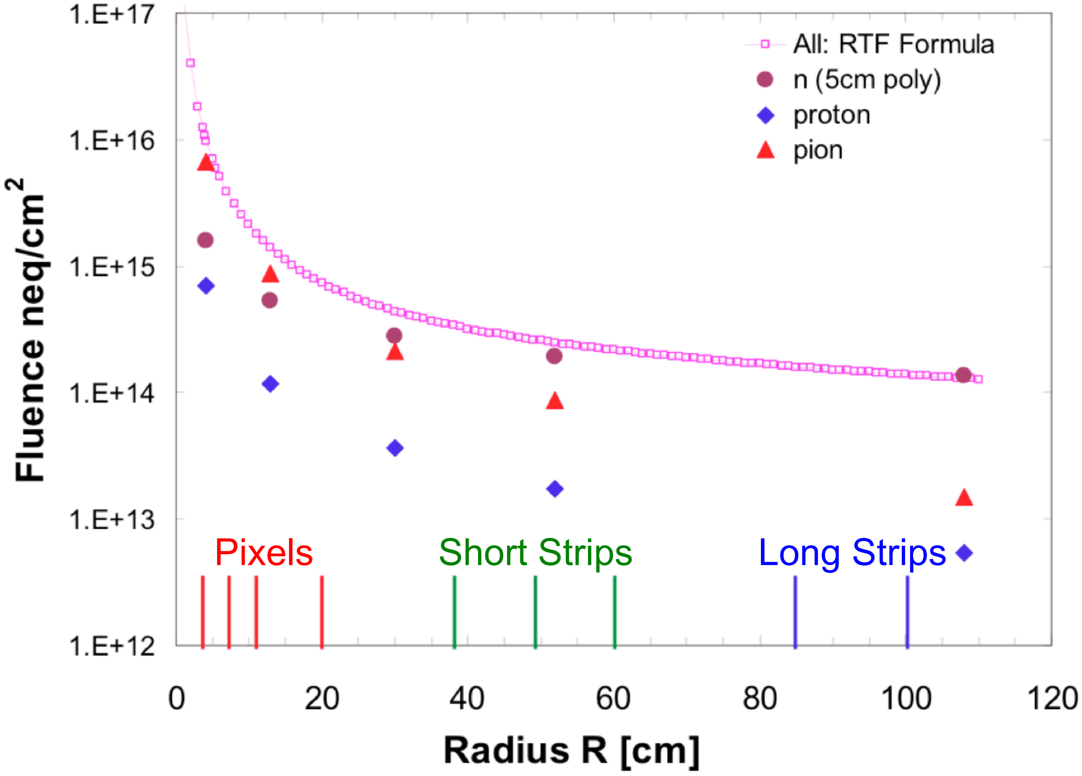
Motivation

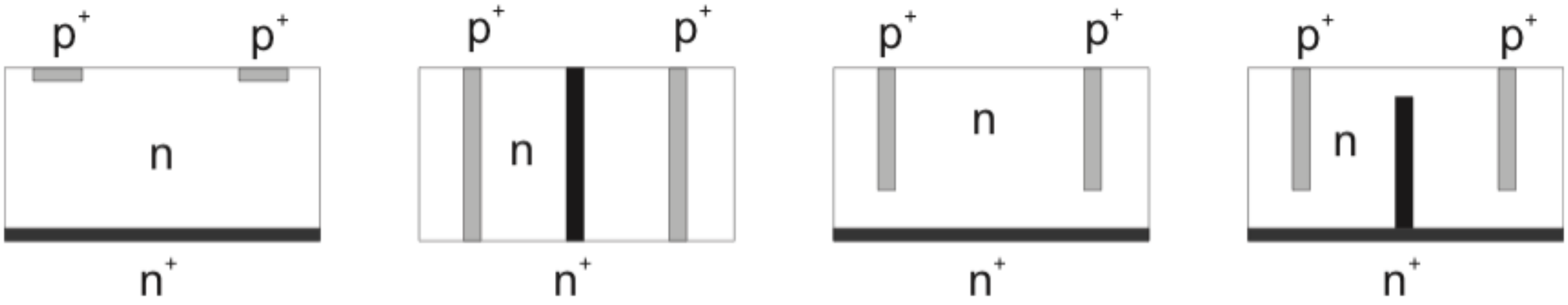
- The planned high luminosity upgrade to the LHC, the sLHC, will increase the luminosity from 1×10^{35} cm^{-2} s^{-1} to 1×10^{36} cm^{-2} s^{-1}
- New radiation-hard detector designs needed to withstand a 10-fold increase in luminosity, with the inner vertex detector being exposed to fluences up to 10^{16} 1MeV n_{eq}/cm^2
- New radiation-hard detector designs are being investigated by the CERN RD50 collaboration
- Among the new detector designs, 3D detectors have been proposed as one of the viable options for the inner pixel vertex tracker



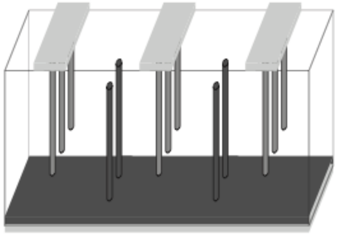
ATLAS Radiation Taskforce [ATL-GEN-2005-01] & H. Sadrozinski [IEEE NSS 2007]

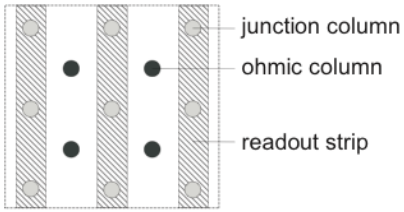
Sensors	Design Fluences (2x safety factor included)
Inner Pixel	1-1.6x10^{16} neq/cm^2= 500 Mrad
Outer Pixel	3x10^{15} neq/cm^2 = 150 Mrad
Short Strips	1x10^{15} neq/cm^2 = 50 Mrad
Long Strips	4*10^{14} neq/cm^2 = 20 Mrad

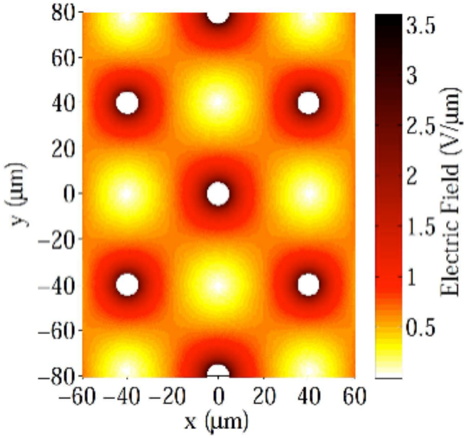
3D Detectors



(a) Planar detector (b) Full 3D (c) 3D STC (d) Double-sided 3D





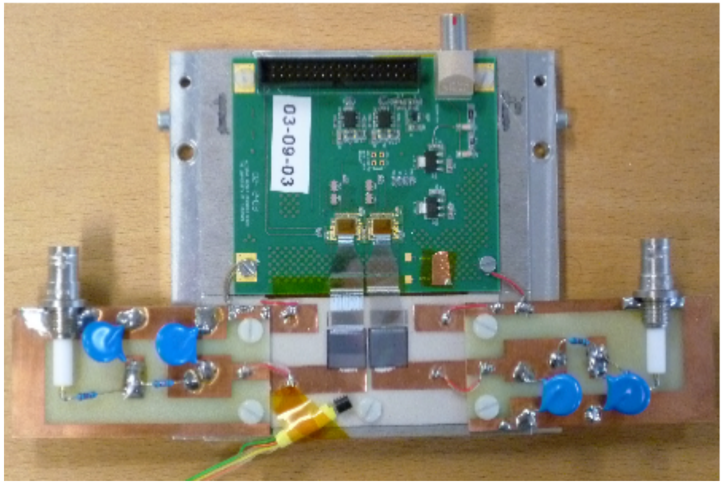


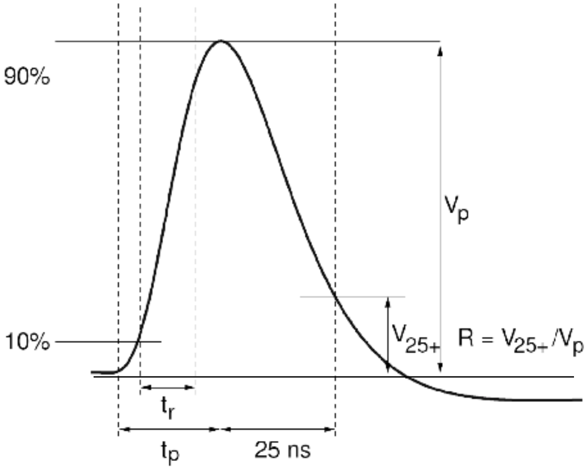
- 3D sensors are designed with p+ and n+ columns inside the substrate
- Lower charge sharing, smaller charge collection length and higher electric fields lead to better performance after irradiation compared to planar sensors
- Although usually designed with pixel readout, 3D strip detector are also produced, making readout much simpler

Manufacurer	Thickness (μm)	Column Spacing (μm)	Column Depth (μm)	Resisivity (kΩ cm)
CNM	285±15	80	jnc. 250, ohmic 250	13
FBK	300±15 (p-in-n) 200±15 (n-in-p)	100 80	jnc. 190, ohmic 160 Jnc. 160, ohmic 160	6 18

ALIBAVA Readout System

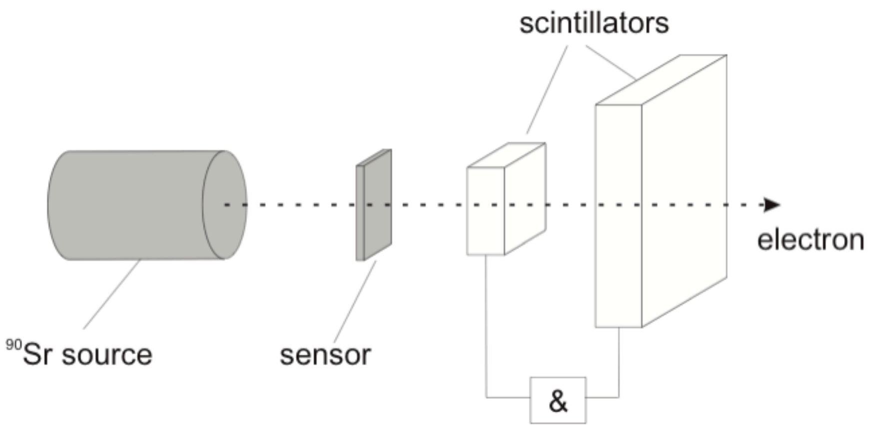
- Charge collection measurements are done through the ALIBAVA readout system
- The daughterboard carries 2 analog front-end ASIC (Beetle) chips, which perform amplification and shaping of the signal
- The analog signal is sent to the motherboard, controlled by and FPGA, and converted into digital counts using a 10-bit ADC (Analogue to Digital Converter)
- The raw data is sent to a PC from the motherboard using a USB connection, and analyzed by custom software based off the ROOT framework

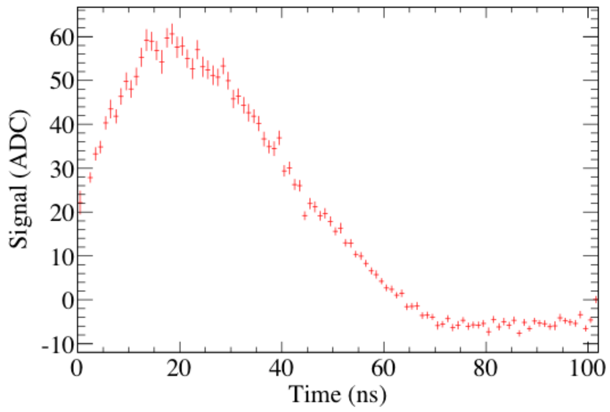


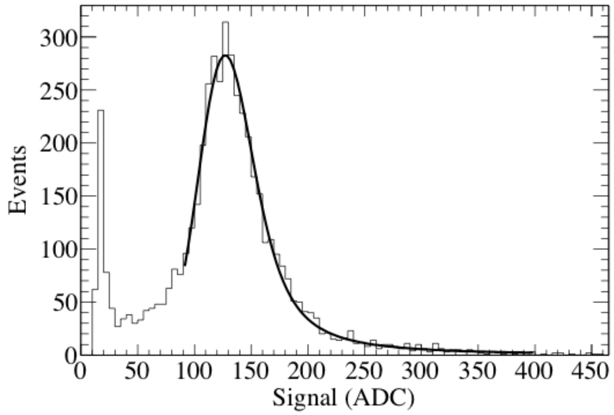


Beta Source Measurements

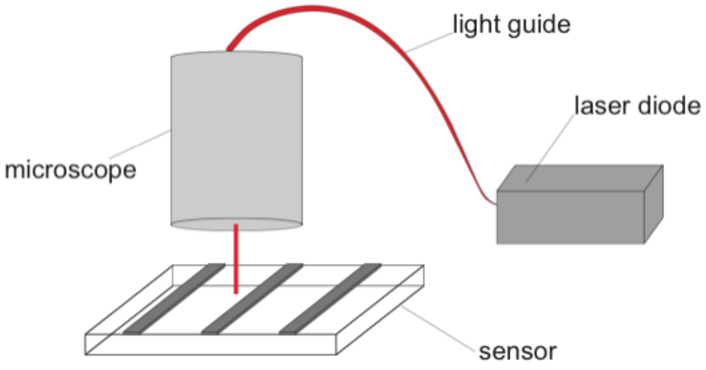
- MIPs from a ^{90}Sr source are used to perform charge collection measurements
- Time between trigger signal and edge of a 10 MHz clock is measured by the ALIBAVA TDC
- For each event, channel with largest SNR is chosen, and mean is calculated for each 1 ns time bin
- Only events in 10 ns window around max are considered
- Resulting spectrum is fitted with a convolution of a Gaussian and Landau distribution to determine MPV

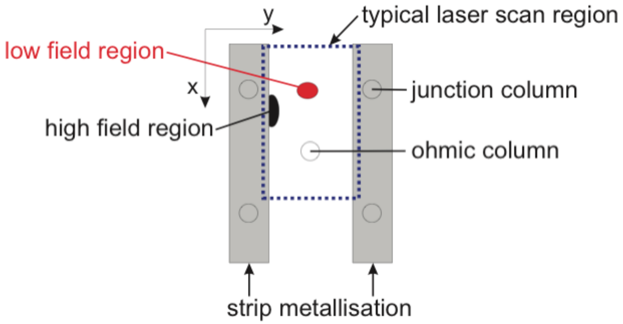




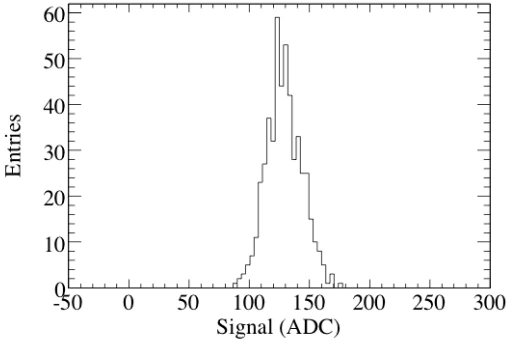


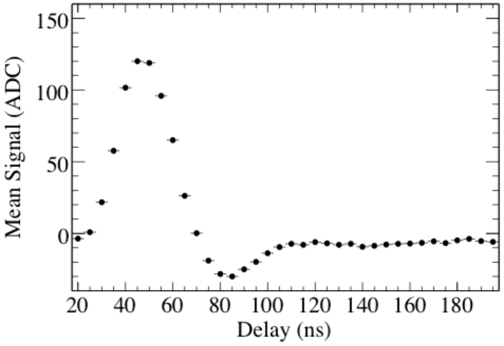
Laser Measurements



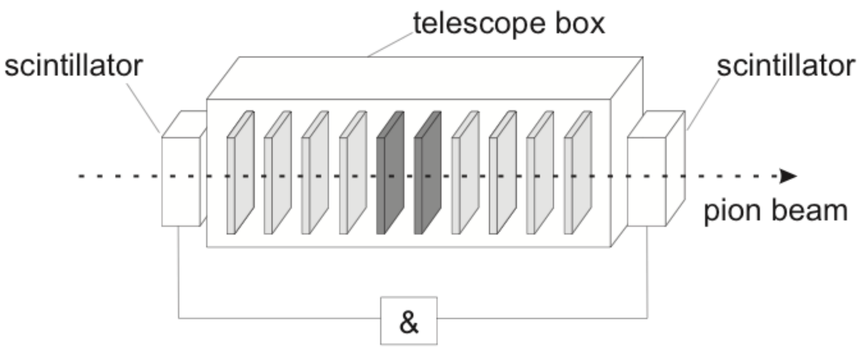


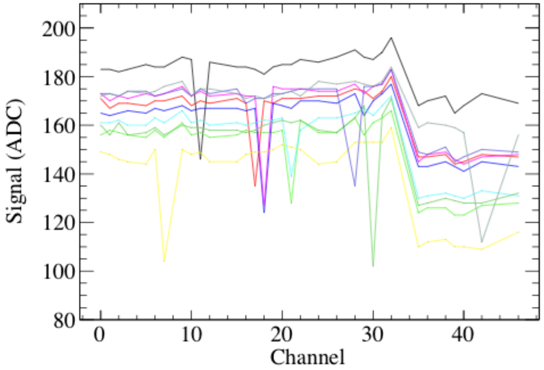
- IR laser is focused on the detector surface with an optical microscope
- Laser spot on surface ~ 3 μm
- IR photons do not penetrate fully through detector bulk, so that only relative position efficiency measurements can be made
- Sensor is held at a constant bias voltage, and the laser is scanned between the aluminum strips
- Laser measurements are used to investigate regions of high and low electric fields

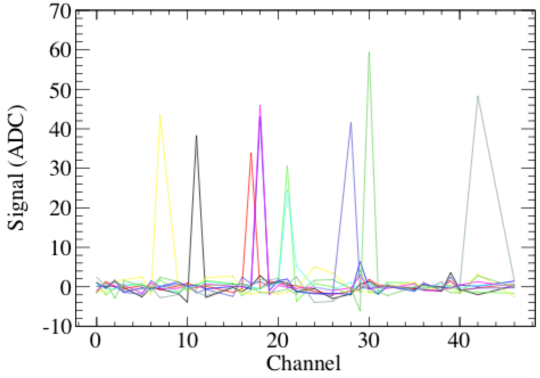




Beam Test Measurements

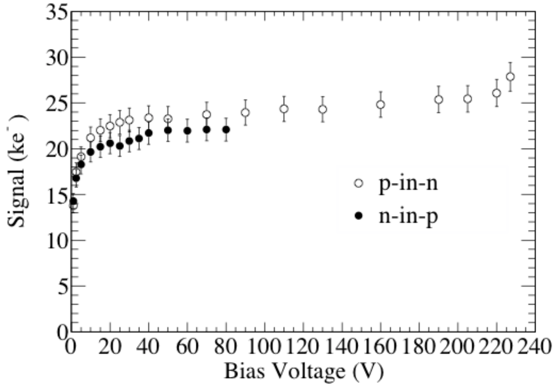


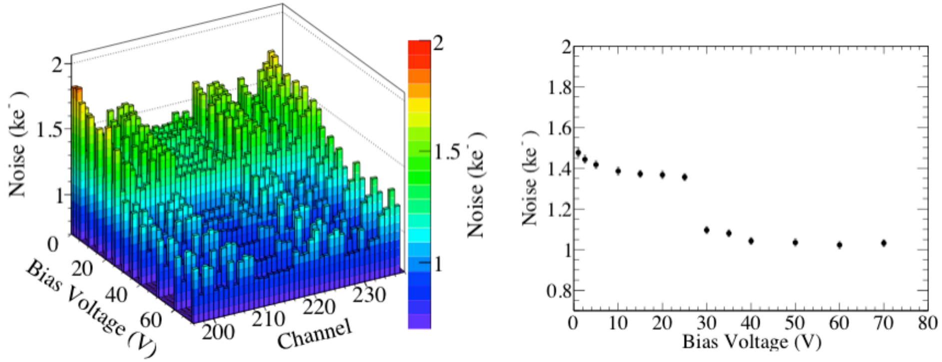




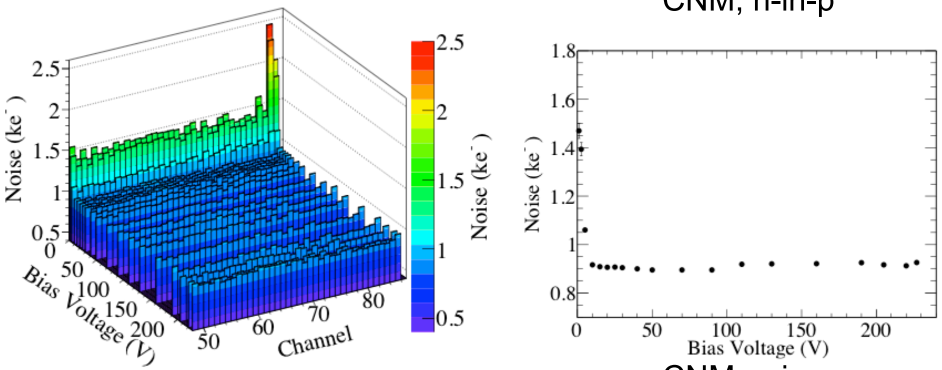
- Beam test used to study detectors in a realistic environment
- Beam composed of 225 GeV pions
- The particle tracks were measured by the Silicon Beam Telescope (SiBT), consisting of eight planes equipped with silicon microstrip detectors
- The devices under test and the reference detectors were positioned perpendicularly to the beam
- Pairs of two detectors are oriented with an angle of 90° to each other, thus the SiBT delivers four reference space points
- Reference tracks have a resolution of approximately 3 μm
- Scintillators at the back and front of the telescope box are used for triggers

Unirradiated Beta Source Results





CNM, n-in-p

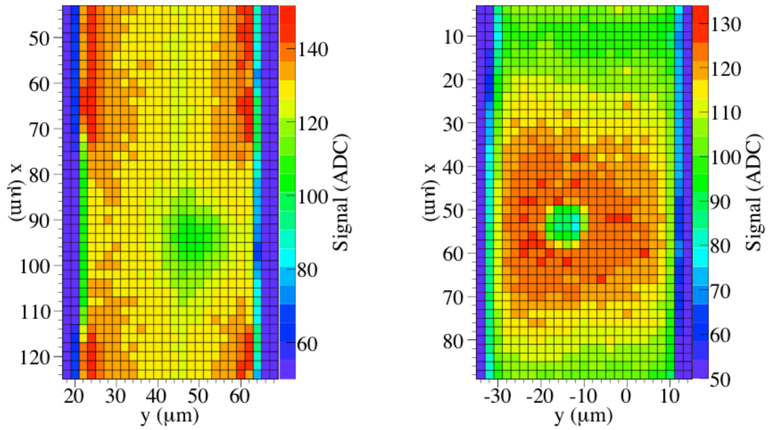


CNM, p-in-n

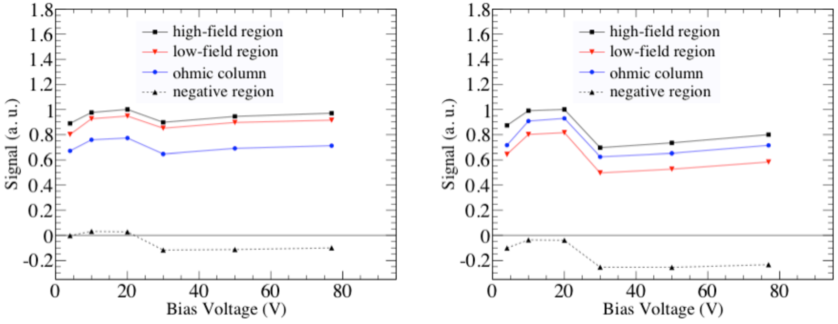
- Both p-in-n and n-in-p sensors have been studied
- Full depletion at V_{bias} ~ 30V
- Onset of charge multiplication can be seen at high bias voltages due to impact ionization
- As the bias voltage increases, the load capacitance decreases, leading to lower noise with increasing bias voltage
- n-in-p sensors show larger noise than the p-in-n sensors, with the difference coming possibly from the p-stop implants present on the n-in-p sensor

Unirradiated Laser Measurement

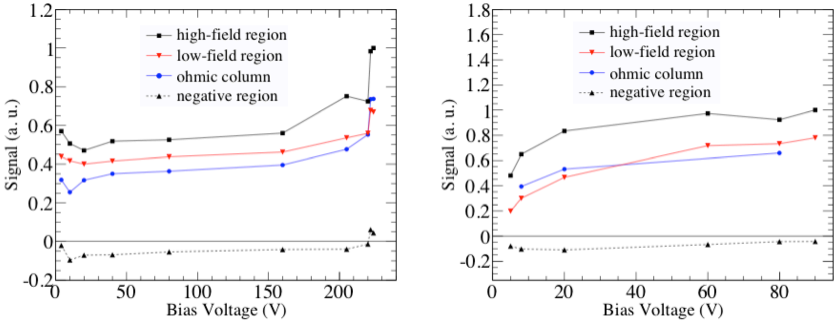
- It is clear from laser measurements that the ohmic columns are displaced from their nominal positions
- Difference in relative signal is seen between four different regions: high-field region, low-field region, ohmic column, and negative region
- Negative regions arise from non-collecting electrodes, where integration time is shorter than the induced current pulse (ballistic effect)



(a) CNM p-in-n, 80 V (b) FBK n-in-p, 80 V



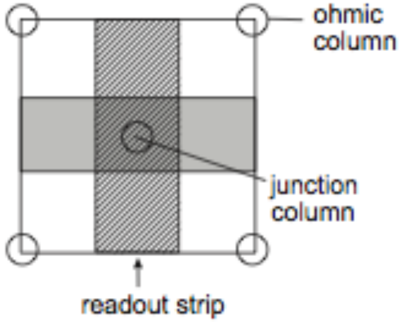
(a) CNM n-in-p, $T = -20\,^{\circ}\mathrm{C}$ (b) CNM n-in-p, $T = +30\,^{\circ}\mathrm{C}$



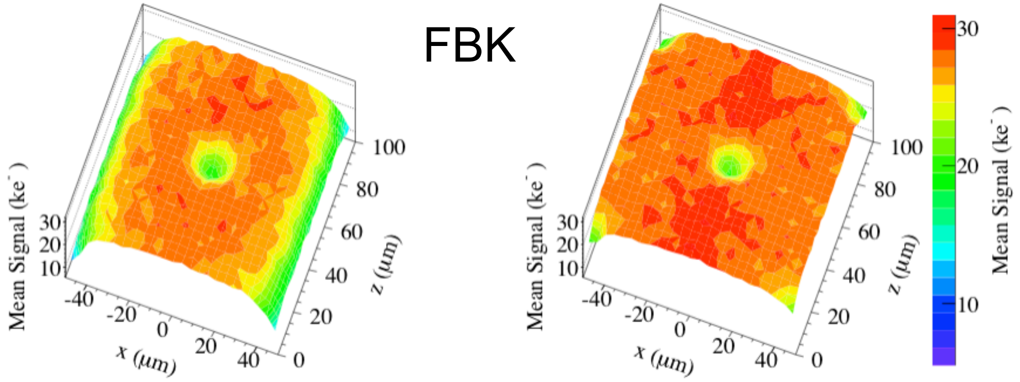
(c) CNM p-in-n, $T = -20\,^{\circ}\mathrm{C}$ (d) FBK n-in-p, $T = +30\,^{\circ}\mathrm{C}$

Unirradiated Beam Test Measurement

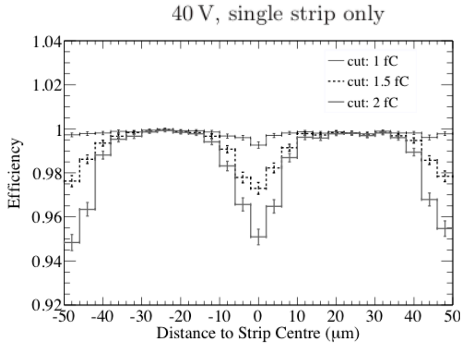
- Unit cell is considered around the readout electrode
- Using different threshold, one can see difference in efficiency in 1D scan centered on the electrode
- Single strip measurements see smaller efficiency in low field regions, but charge sharing can account for this by looking at double strip measurements
- Inefficiency is only present in junction columns when charge sharing is taken into account



FBK

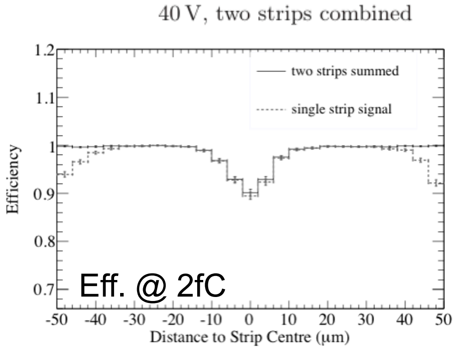


40 V, single strip only



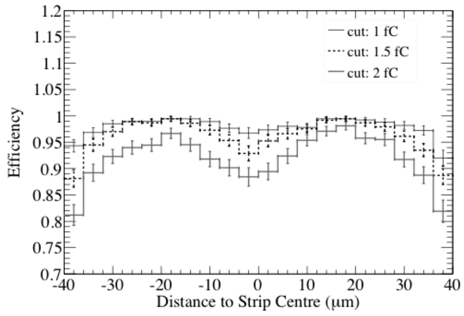
(a) FBK08, 40 V

40 V, two strips combined

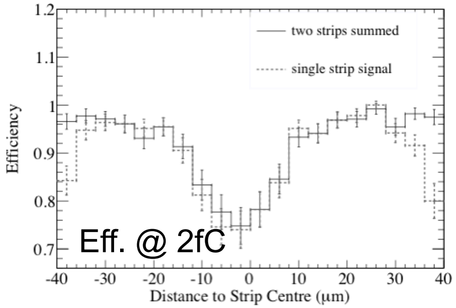


Eff. @ 2fC

(a) FBK08, 40 V



(b) CNM08, 24 V

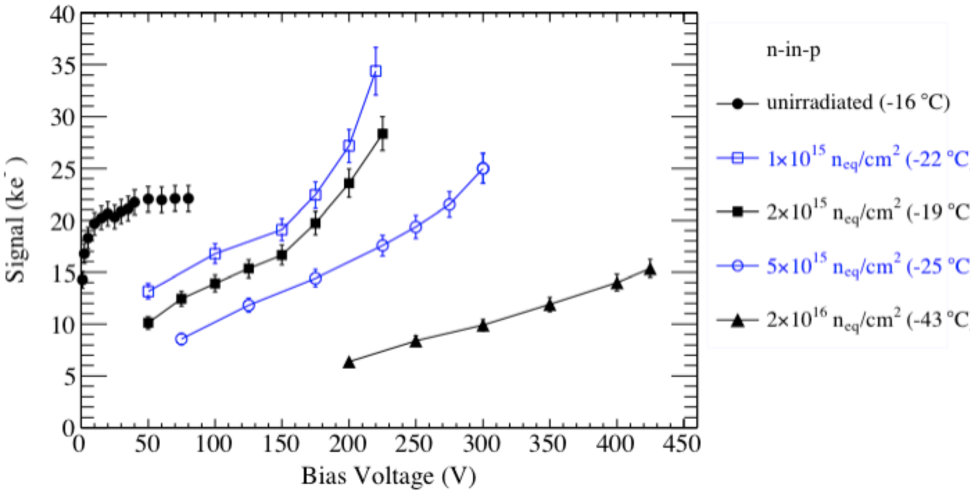


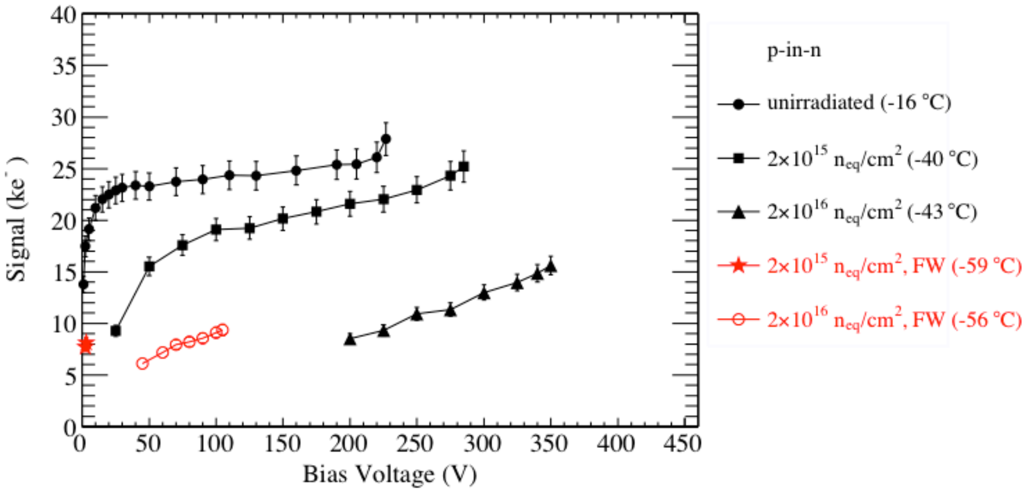
Eff. @ 2fC

(b) CNM08, 40 V

Irradiated Beta Source Measurement

- n-in-p sensors show much larger signal than p-in-n sensors after irradiation
- At 2E15 neq/cm^2 charge multiplication is seen in n-in-p sensors at a V_{bias} of ~150-200V, where p-in-n sensors only show onsets of charge multiplication at much higher voltages ~250-300V
- 3D sensors are shown to be much more rad-hard than planar sensors, with a signal of 15 ke$^-$ measured at a fluence of 2E16 neq/cm^2, compared with a signal of 7 ke$^-$ for planar sensors

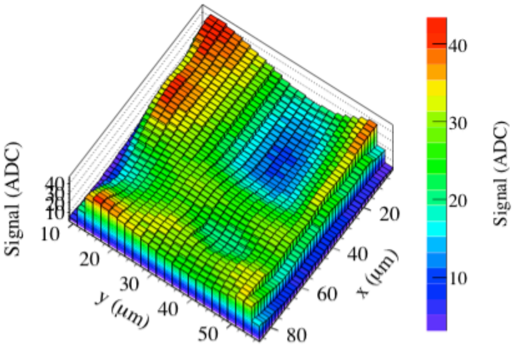




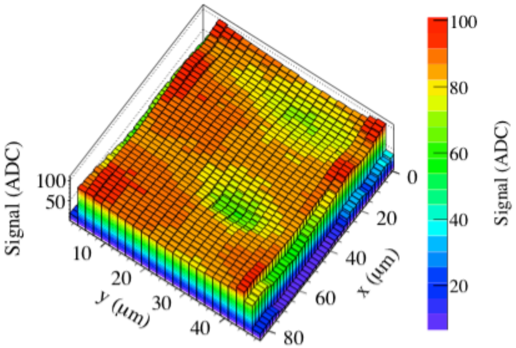
Irradiated Laser Measurement

- Low signal between readout strips is seen at low voltage due to running under depleted
- Large signal increase seen after 150V in all field regions, consistent with CM in Beta measurements
- Much higher CM seen in high field regions due to higher impact ionization rates and reduced trapping

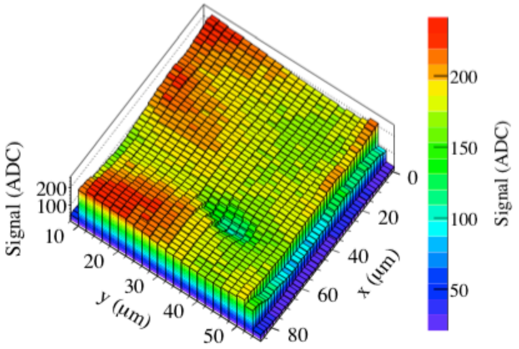
n-in-p, Φ = 2E15 neq/cm^2



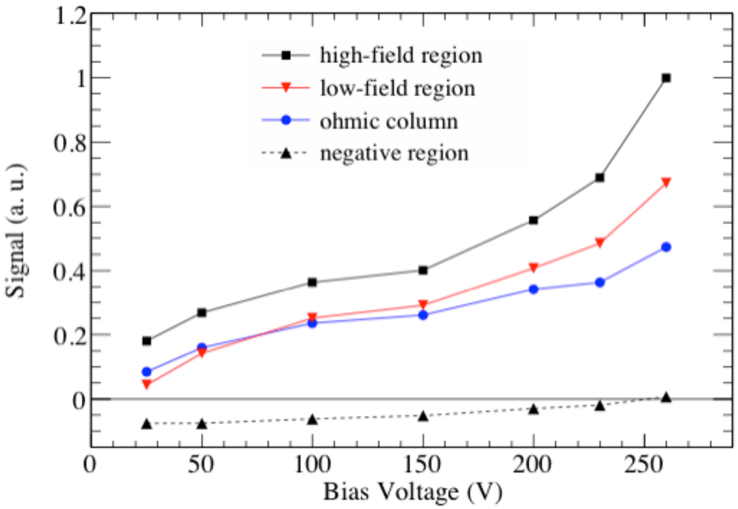
(a) $U = 25\,\mathrm{V}$



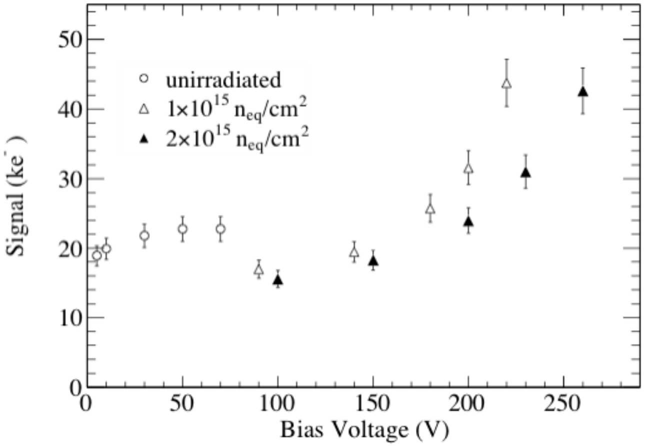
(b) $U = 150\,\mathrm{V}$



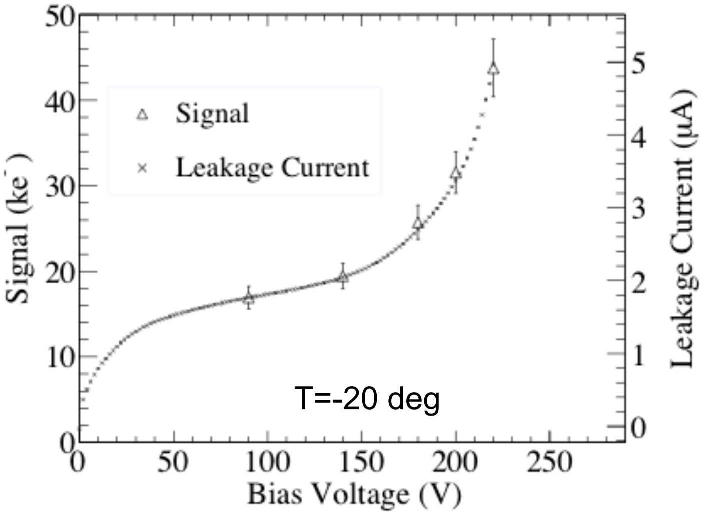
(c) $U = 260\,\mathrm{V}$



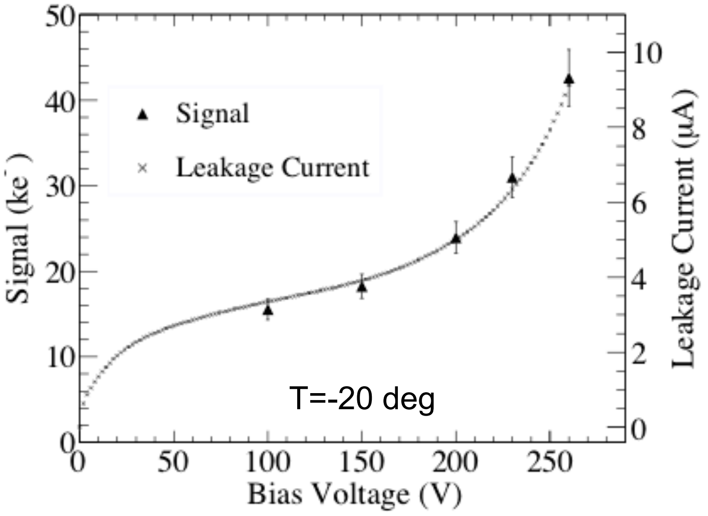
Irradiated Beam Test Measurement



- Charge multiplication confirmed during beam tests
- The measured signal and the leakage current of the irradiated 3D detectors are strongly correlated
- The correlation between the leakage current and the signal shows that charge carriers generated both by traversing particles and by thermal excitation are multiplied by the same factor if the electric field is sufficiently high.

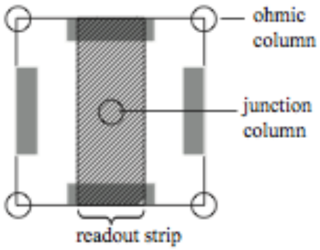


(a) $\Phi_{eq} = 1 \times 10^{15}\ n_{eq}/cm^2$

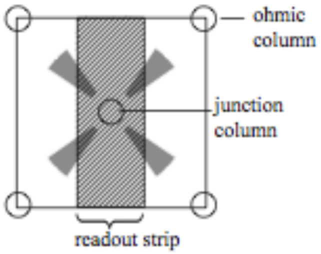


(b) $\Phi_{eq} = 2 \times 10^{15}\ n_{eq}/cm^2$

Irradiated Beam Test Measurement

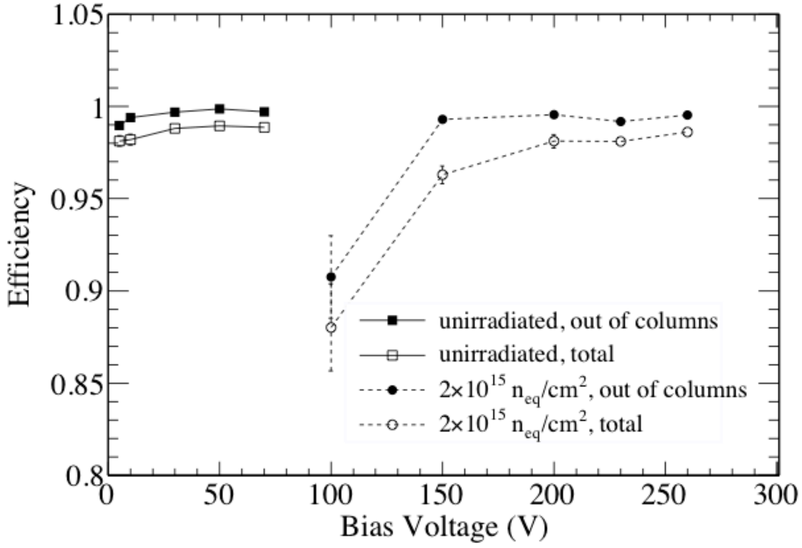


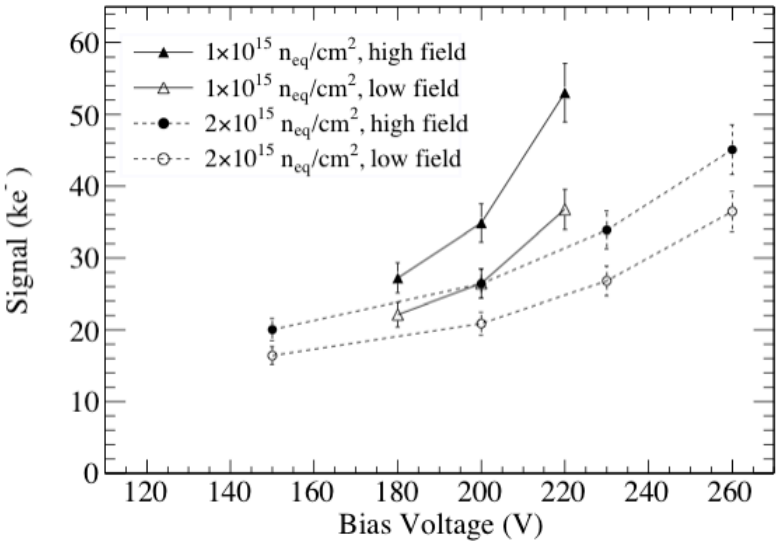
Low Field



High Field

- Charge multiplication is more pronounced in high field regions as expected
- Non-uniformities come from low field regions having longer drift distances and lower drift velocities, increasing trapping probabilities
- Larger efficiencies found when excluding the area of the columns, which constitutes dead area
- Detector efficiency should not be affected much if tracks do not impinge perpendicular to the sensor surface





Conclusions

- Both the signal and the signal uniformity in double-sided 3D sensors is increased compared to 3D single type column (3D STC) sensors, where columns of one doping type only extend into the substrate.

- In the presence of high electric fields, impact ionization can lead to multiplication of liberated charge carriers.

- Measurements of an unirradiated 3D p-in-n detector produced by IMB-CNM showed indications for charge multiplication if bias voltages close to the breakdown voltage were applied.

- These studies are the first measurements indicating charge multiplication in unirradiated silicon detectors designed for tracking purposes in high-energy physics experiments.

- Measurements on irradiated 3D sensors showed great radiation hardness, where charge multiplication on these irradiated devices has be proven.

- With beam tests and laser measurements it could be shown that charge multiplication probably takes place in a thin region around the electrode where electrons are collected.

- The onset of charge multiplication does not lead to a degradation of the spatial resolution.

- At a fluence of 2E16 neq/cm^2, both p-in-n and n-in-p sensors show a large signal of ~15 ke$^-$ at a relatively low voltage between 350-425V.

Extra: Charge Multiplication of Planar Detectors

- Special charge multiplication structures were designed on planar strip detectors by CNM
- Initial measurements on proton irradiated sensors shows signs of CM at 1E15 neq/cm^2, while the effect is harder to see at larger fluences, but still may indicate CM at 5E15 neq/cm^2