Proton-Induced Degradation in High-Resolution Geiger Tracking Detectors

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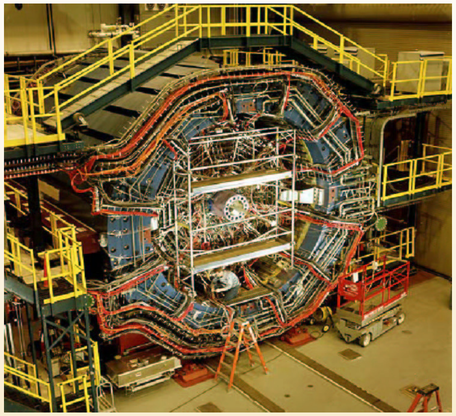
Outline

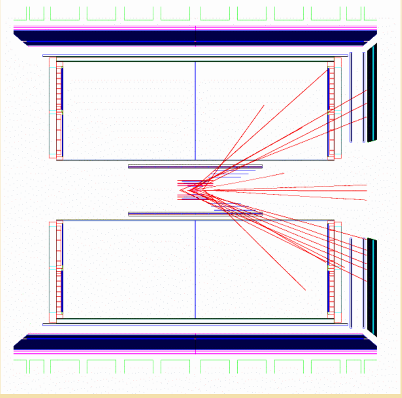
- High-resolution tracking (microvertex) detectors
- How the Geiger avalanche detector works?
- Potential advantages of using Geiger sensors for high-resolution tracking
- Irradiation protocol
- Results
- Conclusions

Geiger sensor development at aPeak

- Funded by the DOE, NP division, we have recently prototyped high-resolution tracking Geiger sensor arrays for microvertex detectors (see paper N45-5)
- We present the preliminary evaluation of Geiger sensor degradation after irradiation with 55 MeV protons
- We use high-volume manufacturing CMOS and in-house developed Geiger sensor layout libraries to fabricate a wide variety of single-photon and single-electron sensor arrays for applications ranging from HEP/NP to biomedical applications
- The process is extremely robust, the reliability of the process/layout design was quantified over three years of continuous operation with little performance degradation
- Besides sensor arrays for high-resolution tracking we developed and marketed Geiger photodiode (GPD) arrays spanning over a wide range of pixel sizes: from 13 μm to ~1mm
- The size of the largest array is 10mm x10mm and contains 64 x 1mm pixels (see poster N30-216 (11/1)

High-resolution tracking microvertex detectors



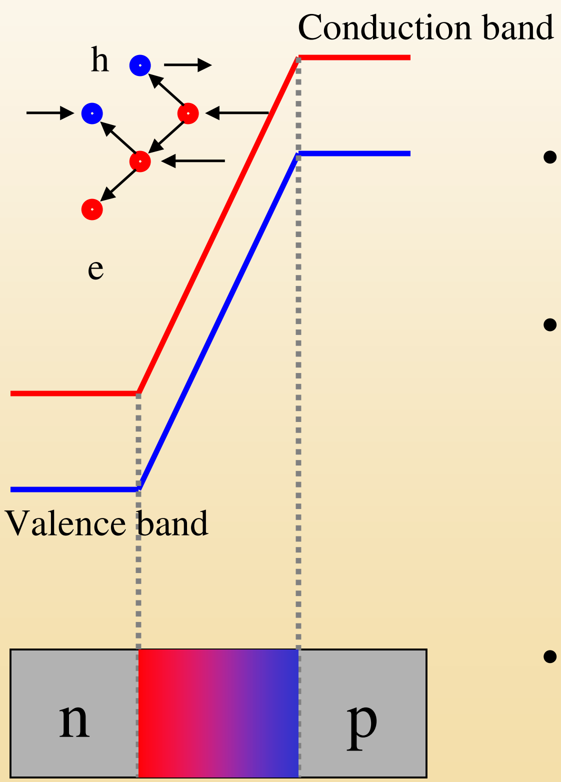


- High spatial resolution microvertex detectors must provide accurate measurements of particle tracks very close to the interaction point.
- Track reconstruction allows to recognize the formation of very short lived particles, such "b-hadrons"
- These particles have lifetimes of around 1psec and travel only a few mm before decaying: therefore microvertex detectors must be positioned within less than approximately 10 mm to the beam and should be capable of 10 μm spatial resolution
- Thin detectors are needed to avoid charged particle scattering and consequently loss of resolution
- The detectors have to operate at relatively high fluence

Courtesy of Brookhaven National Laboratory

How the Geiger avalanche sensor works?

Historically, the use of the Geiger avalanche for charge detectors was proposed in 1956 by Haitz. Advances in and easier access to silicon processing, as well as the inherent high-gain in such detectors, has sparked a renewed interest in using the Geiger avalanche for single-electron and single-photon detection



- Geiger detectors are p-n junctions reverse-biased above the breakdown voltage, designed to undergo bulk avalanche breakdown
- Free carriers are accelerated in the electric field, create secondary e-h pairs and may initiate the Geiger avalanche
  - Typical avalanche volume in our high-resolution tracking detectors ≈ $30\mu m^3$
  - Charge gain ranges from 10^6 to 10^7
  - Operation voltage ≈ 13.8V at room temperature
- Main Geiger sensor performance parameters:
  - Dark count rate DCR = DCR (V,T) V=bias, T=temperature
  - Detection efficiency DE= DE(V, n_e,T) n_e = nr. electrons crossing the p-n junction

Advantages of using Geiger sensors for high-resolution tracking

- Due to the internal gain ($>10^6$) and high detection efficiency of minimum ionizing particles (MIPs), Geiger sensors generate higher charge/MIP as compared to unity-gain high-resolution silicon tracking detectors, and therefore the readout noise decreases dramatically (thus results in higher frame rate)
- The integration time is much shorter than in unity gain tracking detectors (ns as compared to μs)
- The detection efficiency at typical charge deposited by MIPs is 100%
- As compared to CMOS Active Pixel Sensors (APS) Geiger sensors are immune to surface degradation and therefore should have a superior radiation tolerance/hardness

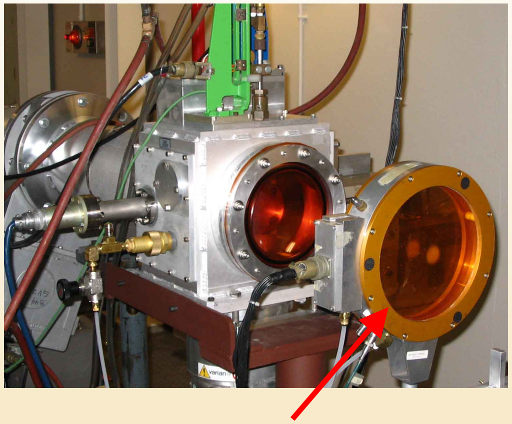
Geiger avalanche sensors - radiation hardness

- Charged particle-induced damage in avalanche sensors (photodiodes), biased BELOW the breakdown voltage, has been previously measured by Becker (IEEE TNS, p.1974, 2003), Swanson (IEEE TNS p.1658, 1987)
- There is little information on irradiated p-n junction sensors biased ABOVE the breakdown voltage in Geiger mode
- Questions we would like to answer in the long term:
  - How much degradation of the DE and DCR we should expect in Geiger sensors?
  - What are the competing damage and damage annealing mechanisms?
  - How to model the performance of irradiated Geiger sensors and how to use the modeling as a tool to improve their radiation hardness?

–How much degradation of the DE and DCR we should expect in Geiger sensors?

Irradiation and Testing Protocol

Source: LBNL

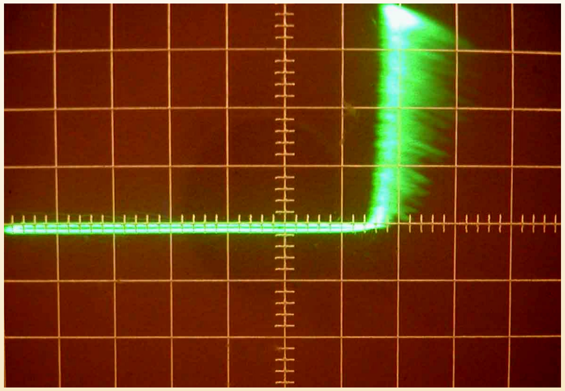


Ion chamber beam monitor

In-beam uniformity was measured with an ion chamber using 6 rings. Beam was adjusted to maintain ring currents within 10% uniformity.

- Irradiation run at Cyclotron 88", LBNL
- Proton fluence: 1.7E8p/(cm^{2}x sec)
- Proton energy: 55MeV
- Proton dose: 1E11, 3E11 p/cm^2
- 25 Geiger pixels/dose 13 micron diameter were tested for DCR and DE before, 30 days, and 224 days after irradiation

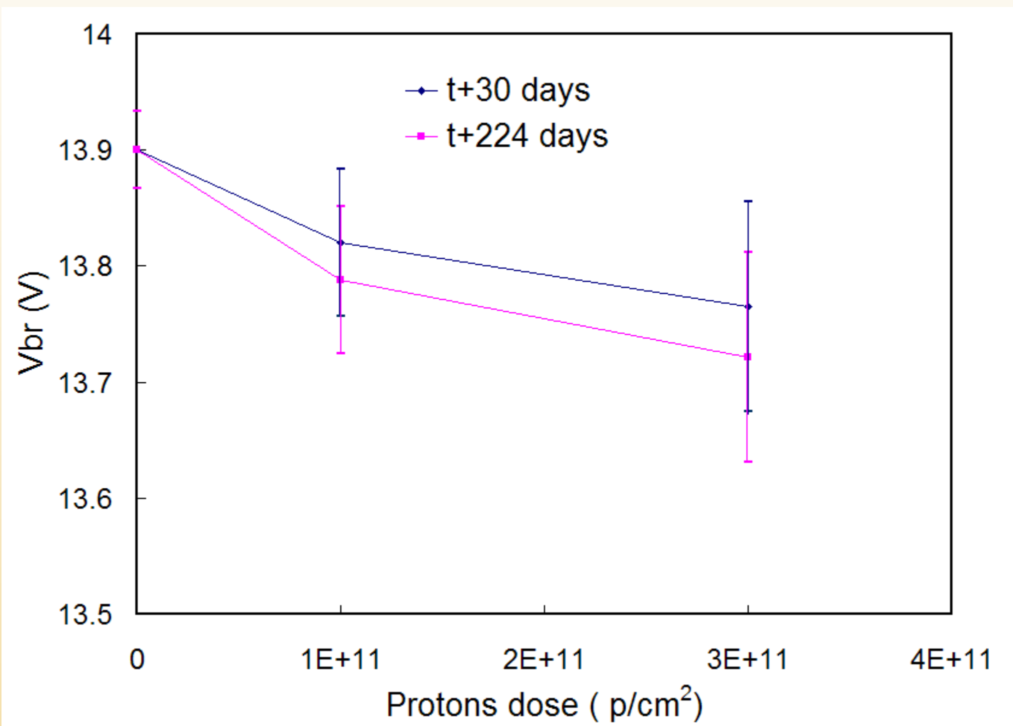
Post irradiation Geiger I-Vs



Reverse I-V of irradiated GPD pixels at $3x10^{11}$ p/cm^2 shows a sharp breakdown and characteristic Geiger event flares (horizontal scale: 2V/div).

The flares are typical for low noise bulk avalanche breakdown and indicate the capability of quenching Geiger events for pixel bias up to 2 V above the breakdown voltage

Breakdown voltage



Over this dose range, the breakdown voltage decreases at a by 120 mV

Vbr statistical spreading is too large to infer any trend after 224 days of annealing

RT DCR degradation & annealing

•DCR in Geiger sensors is a high sensitivity monitor of the performance degradation

•Dark Geiger counts are generated when single charge carriers (electrons or holes) cross the avalanche junction

•Monitoring DCR allows to detect damage in the semiconductor volume

DCR at constant voltage above breakdown ($V-V_{br}$) was measured on 25 pixels/dose at room temperature before and after irradiation

As compared to the degradation of the dark current in avalanche photodiodes biased below breakdown (100x-400x increase[1]) the DCR for our Geiger sensors increased by only 15x for the same dose (3E11p/cm²)

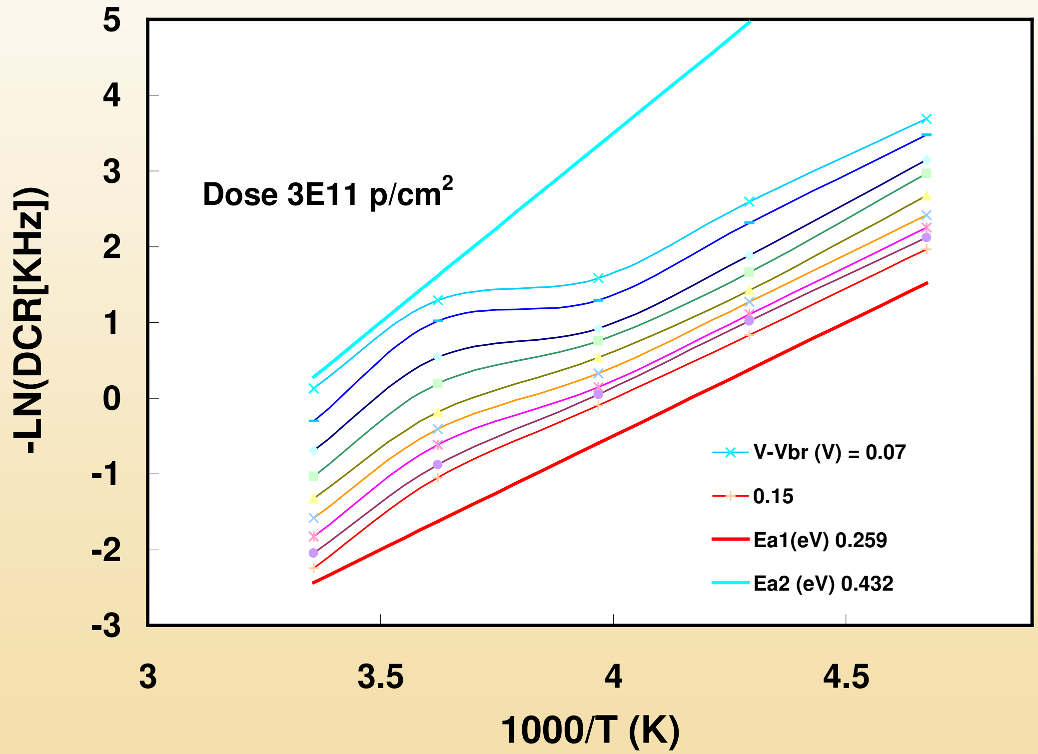
t + 30days	Average DCR (KHz)		DCR Increase
Dose (p/cm²)	Before	After	
0	0.99		
1.00E+11	1.04	6.05	5.8
3.00E+11	1.11	15.2	13.7

t +224 days	Average DCR (KHz)		DCR Increase
Dose (p/cm²)	Before	After	
0	0.99		
1.00E+11	1.04	2.43	2.3
3.00E+11	1.11	10.43	9.4

Annealing (%)	
Dose (p/cm²)	
1.00E+11	59.8
3.00E+11	31.4

[1] Becker, IEEE TNS, p.1974, 2003

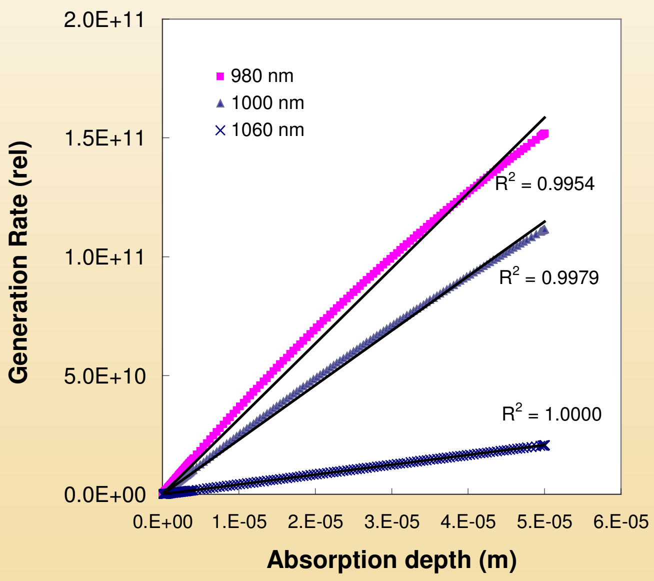
Activation energy of irradiated samples



Low activation energy in the hump at lower bias suggests a contribution of tunneling to the thermal generation in the space charge region (Bogaerts, IEEE TNS, p.1515, 2001 shows similar field enhanced contribution to the dark current after irradiation with 1E11p/cm^2)

Detection Efficiency Measurement

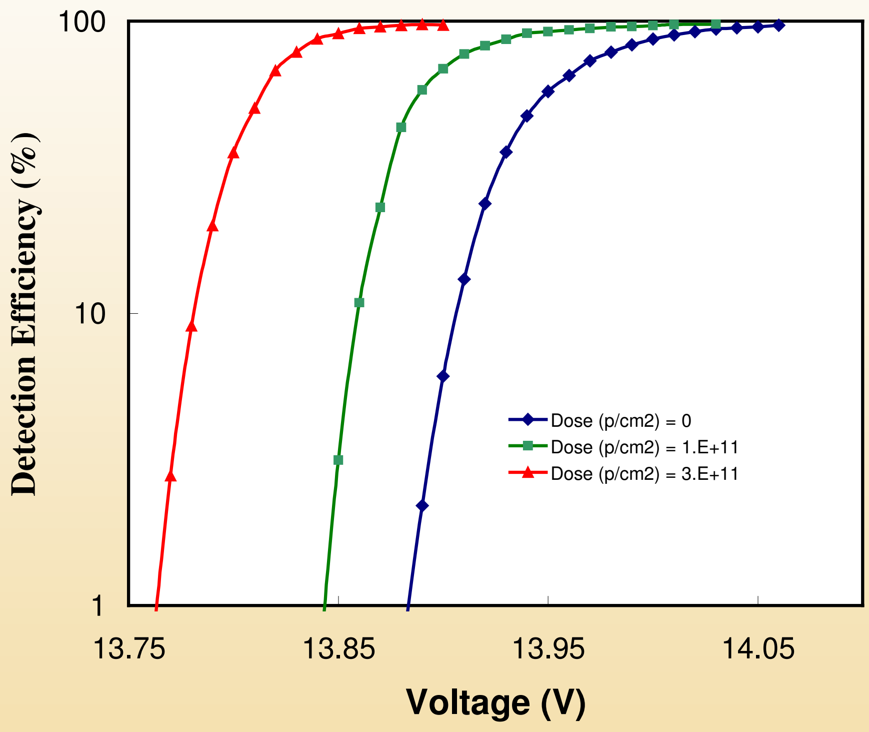
MIP energy loss is quasi-constant and generates in Si about 80 e-h pairs/µm



- 1060 nm photons generate e-h pairs at constant rate (see modeling results) and could be used for laboratory evaluation of microvertex detector response to MIPs
- 50 µm thick detectors at 2% quantum efficiency for 1060 nm would collect about 80 e-h pairs through the Geiger avalanche junction
- DE was measured at 80 photo-carriers/event using a 1060nm pulsed laser beam, 12µm FWHM

Pulsed 1060nm laser diode

Detection efficiency DE vs. dose



No degradation of the DE occurred after irradiation

Conclusions

- We confirm that small pixel Geiger sensor arrays for micro vertex detectors are radiation tolerant and they are fully functional after irradiation with 55 MeV protons up to a dose of $3x10^{11}p/cm^2$
- The room-temperature breakdown voltage decreases by only 120 mV after irradiation
- The dark count rate increases from 1KHz to 15KHz and anneals 0.15%/day for $3x10^{11}p/cm^2$
- No degradation of the intrinsic detection efficiency occurs up to $3x10^{11}p/cm^2$
- In irradiated devices, tunneling may be responsible for both breakdown voltage decrease and low activation energy of the dark count rate at low bias