CEPC Fast Luminosity Detector design using SiC

Xiyuan Zhang[1] , Yanpeng Li[1,2] , Haoyu Shi[1], Dou Wang[1], Meng Li[1,3] ,

Philip Bambade[3],Weimin Song[2] and Xin Shi[1]

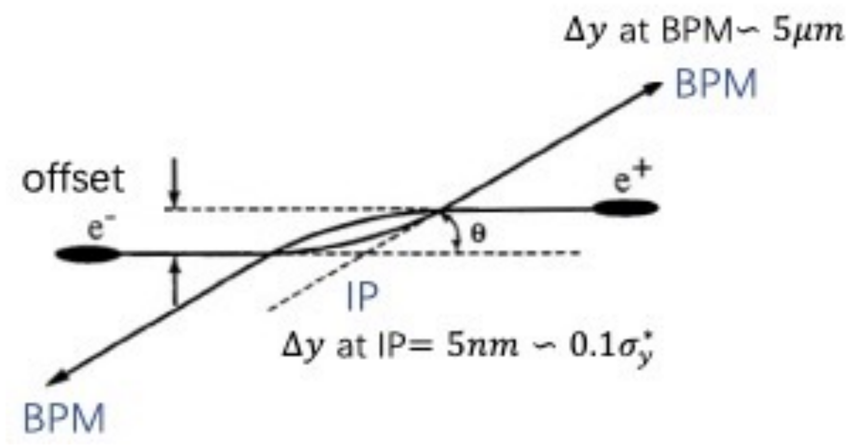
[1]Institute of High Energy Physics, CAS
[2]Jilin University
[3]Laboratoire de l'Accélérateur Linéaire (LAL),Centre Scientifique d'Orsay

Necessity of the Fast Luminosity Monitor for CEPC

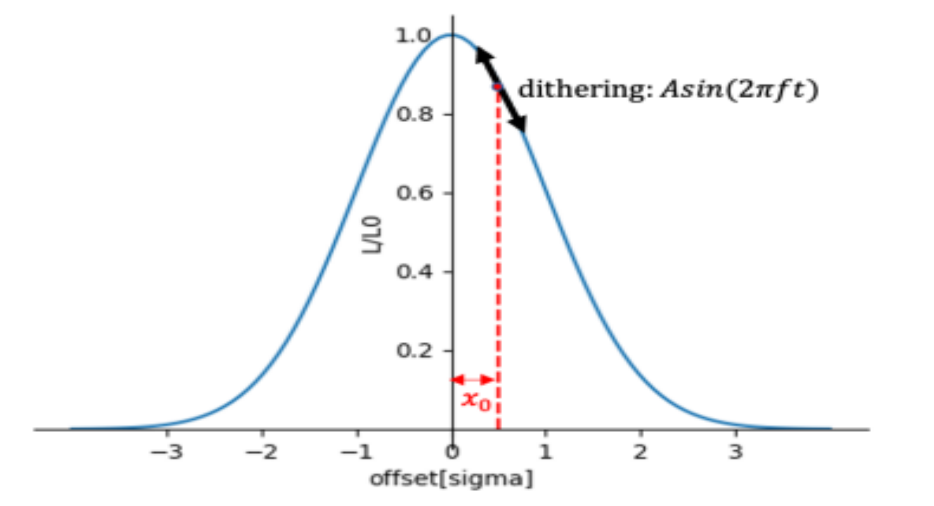
Meng Li from accelerator

- Crab waist scheme for CEPC to achieve a very high luminosity (5×10^{34} cm^{-2}s^{-1})
  - IP beam size very small
  - Luminosity sensitive to the stability of beam jitter (like ground motion)
- Orbit feedback system at the IP to maintain an optimum collision and maximize the luminosity
- Two possible methods for the IP orbit feedback system

Vertical IP orbit feedback——**Beam-beam deflection driven method**



Horizontal IP orbit feedback——**Luminosity driven method**

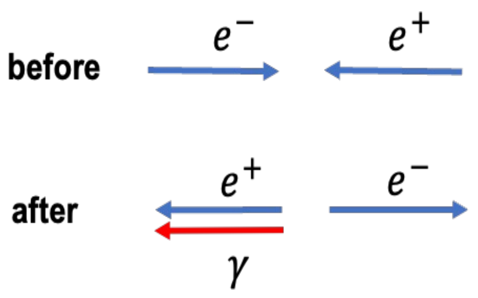


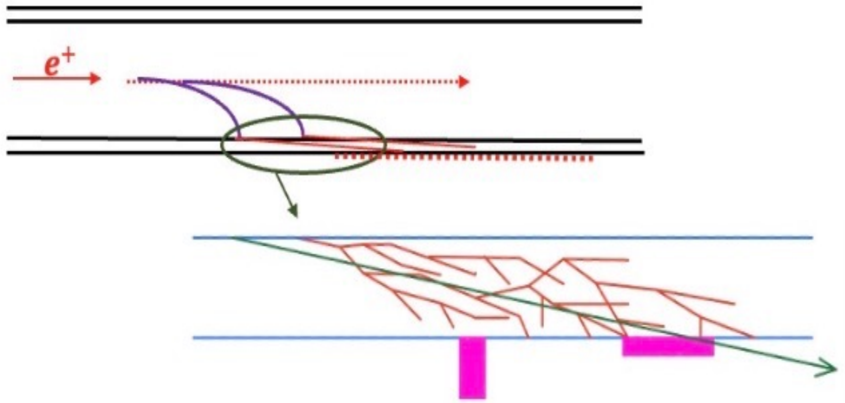
- **Insufficient BPM resolution in the horizontal plane, a luminosity-driven dithering feedback system required**

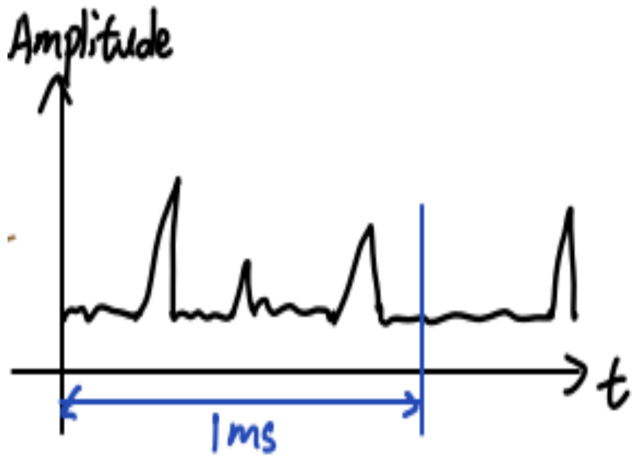
Fast Luminosity Monitor working principle

Meng Li from accelerator

- The fast luminosity monitor based on radiative Bhabha at zero degree
  - Very large cross section (127mbarn)
  - Bhabha particles produced at the IP are proportional to the luminosity







$$N = \sigma \times \mathcal{L} \times \tau \times \epsilon \qquad v = \frac{1}{\sqrt{N}}$$

- The low energy Bhabha hit the vacuum chamber downstream of the IP
- The detectors put outside the beam pipe measuring the secondary particles to provide the luminosity information
  - Number of Bhabha sensitive to the change of luminosity in proportion way (relative luminosity measurement)

Luminosity	Cross section	Number of Bhabha	Aimed precision	Required fraction
5×10^{34}	0.127 barn	6.35×10^6 in 1ms	2% in 1ms	4×10^{-4}

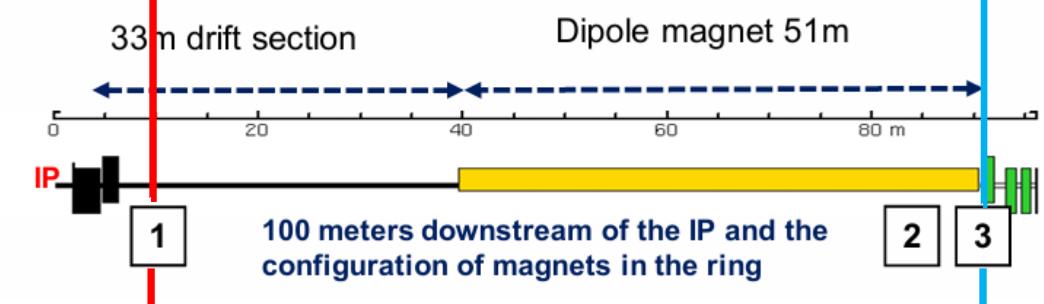
$$\Delta N = L\times\sigma\times T\times f \Rightarrow \boldsymbol{L} \propto \Delta\boldsymbol{N}$$

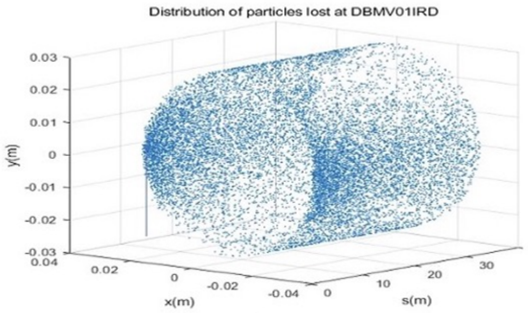
- Precision requirement: $\nu \leq$ 2% @1khz （Number of detected Bhabha electrons $N_d \geq 2500$ ）

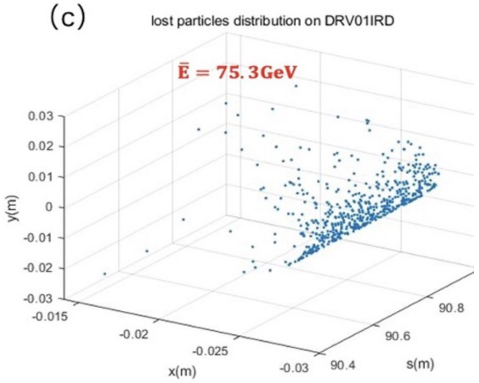
The position of Fast Luminosity Monitor

Meng Li from accelerator

- Low-energy scattered electrons are mainly lost at Position 1、2 and 3
- Positions 1 and 3： suitable for detector installation
- Position 2 excluded： not feasible for detector installation （inside the dipole magnet）







	Position1	Position2	Position3
Distance from IP	10m	84m	90.5m
Average Number detected/collision	3.4(two sides)	3(one side)	3.2(one side)
Average Number detected/ms	2830	2500	2670
Expected Measured Precision	1.9% @1kHz	2.0% @1kHz	1.9% @1kHz
Average Energy of scattered electron	24GeV	70GeV	75.3GeV
Average Hitting Angle	$1.7 \times 10^{-4} rad$	$7 \times 10^{-4} rad$	$7 \times 10^{-4} rad$
Maximum Secondary Particle Position	88mm	104mm	105mm
Detection Area	$5 \times 20 cm^2$	$3 \times 15 cm^2$	$3 \times 15 cm^2$
Backgrounds	SR Photons in 1 Side	-	-
Beam-Beam Deflection Impact	sensitive	less sensitive	less sensitive
Detector Number	2	1	1
Detector Measurement Parameters	Number of signals within 1ms		
Detector Time Resolution	600ns		
Detector technology possibility	LGAD, SiC, Diamond		

[DOI： https://doi.org/10.1007/s41605-024-00491-8]

Silicon carbide

Wide band material Silicon Carbide(SiC) as particle detector material:

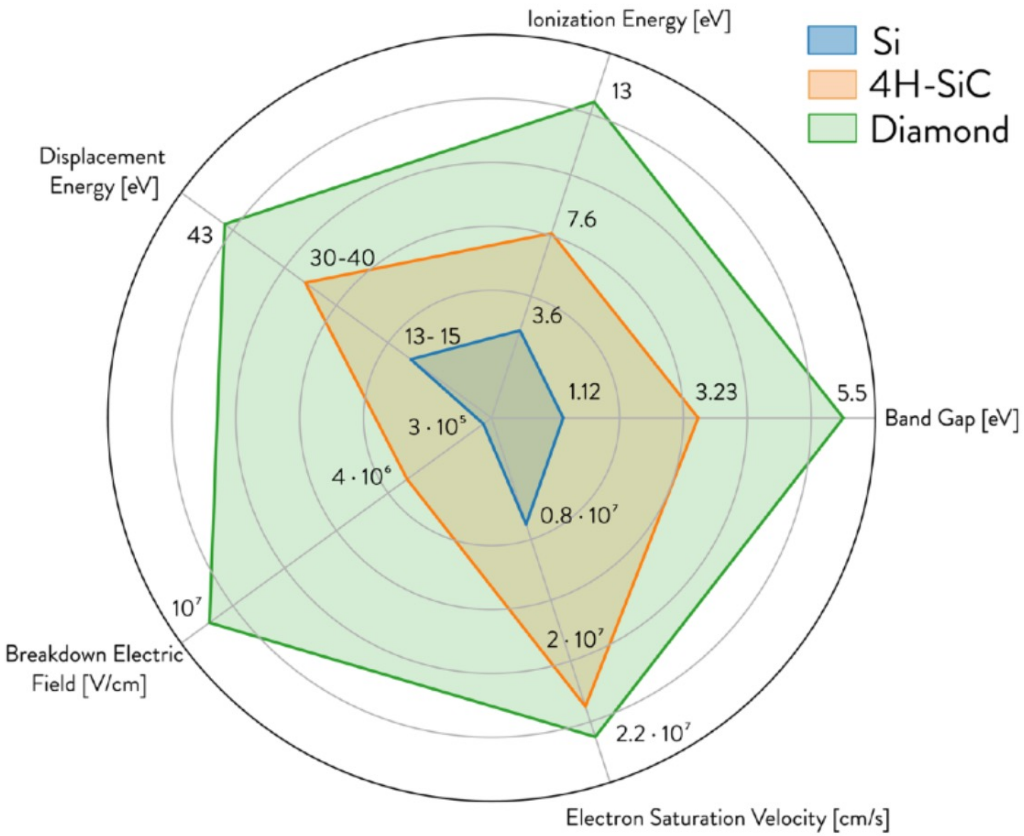
- **Pros:**
  - Bandgap between silicon and diamond
  - Higher saturation velocity and breakdown field
  - Larger atomic displacement threshold

  → Potentially good radiation hardness
  - No dark current increase after irradiation
  - High thermal conductivity

  → No cooling needs
  - No sensitivity to visible light

- **Cons:**
  - Different polytypes(3C, 4H, 6H)
  - Higher ionization energy

  → Smaller signals → LGAD
  - Epitaxial-grown limited to ~150µm thickness

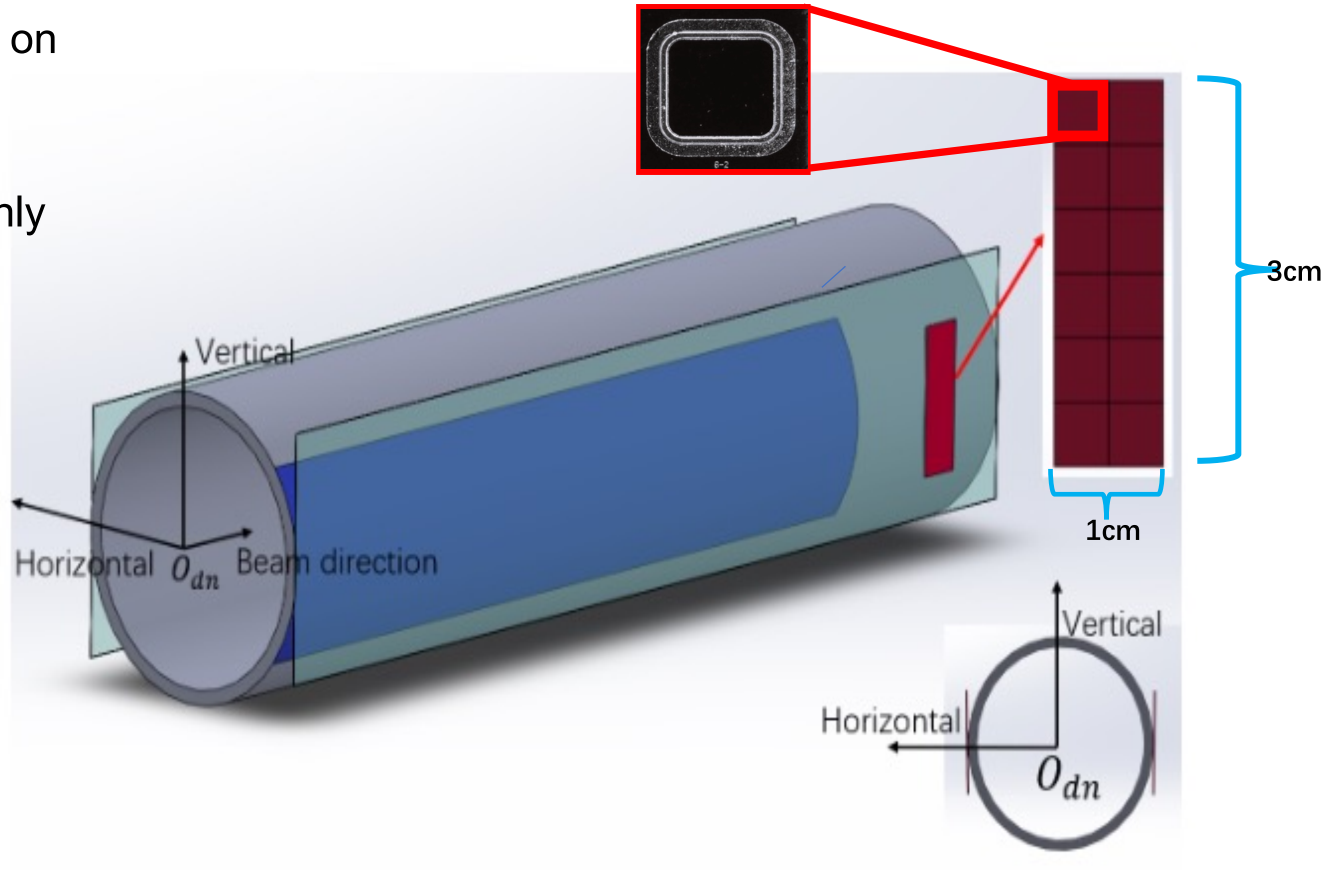


[Front. Phys., 2022]

Detector Geometry & Layout Optimization

- Detector layout
  - Position1: **double detectors** - symmetrically on inner and outer of beam pipe
  - Position3: **single detector** – on outer side only

- Detector dimension :
  - Total Size: 1 cm (beam) × 3 cm (vertical)
  - 2 × 6 pixels
  - Unit size: 5 mm × 5 mm per pixel

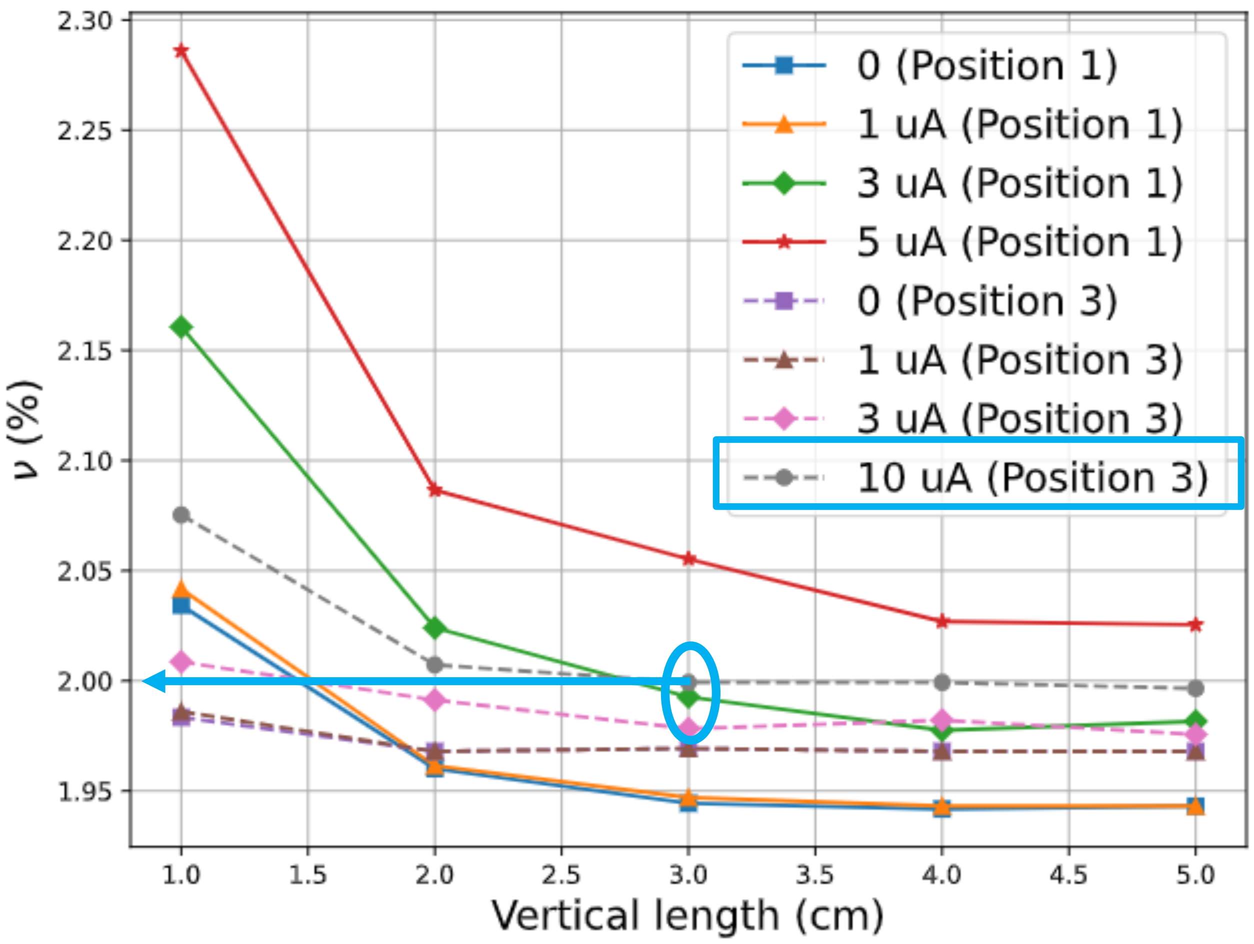


Detector Geometry & Layout Optimization

- Optimal choice: **Position 3**
  - Reach 2% relative precision

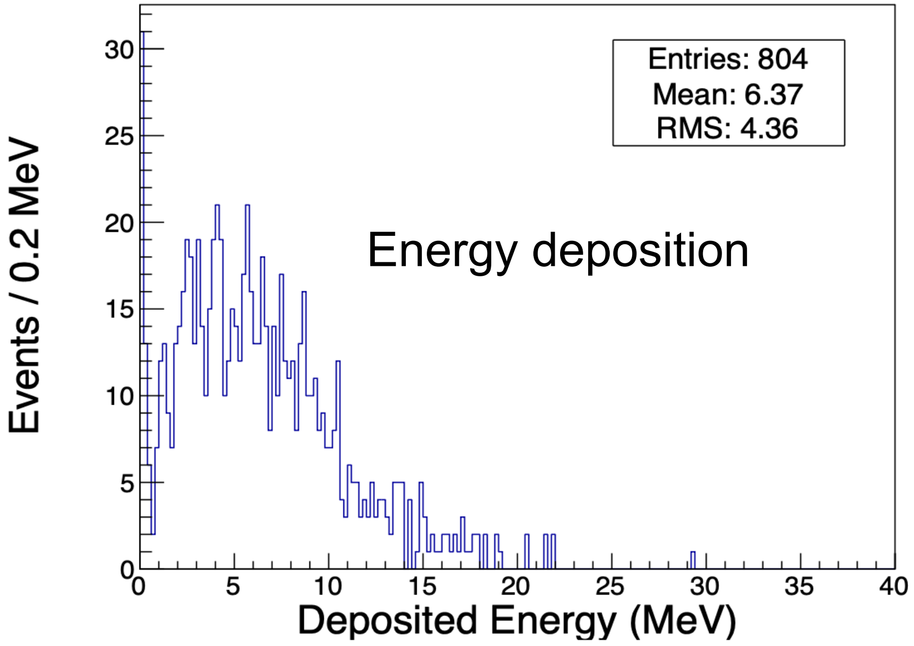
    @ 1 cm (beam) × 3 cm (vertical)
  - Single sided placed
  - Lower noise requirement < 10μA
  - Unaffected by beam-beam deflection and synchrotron

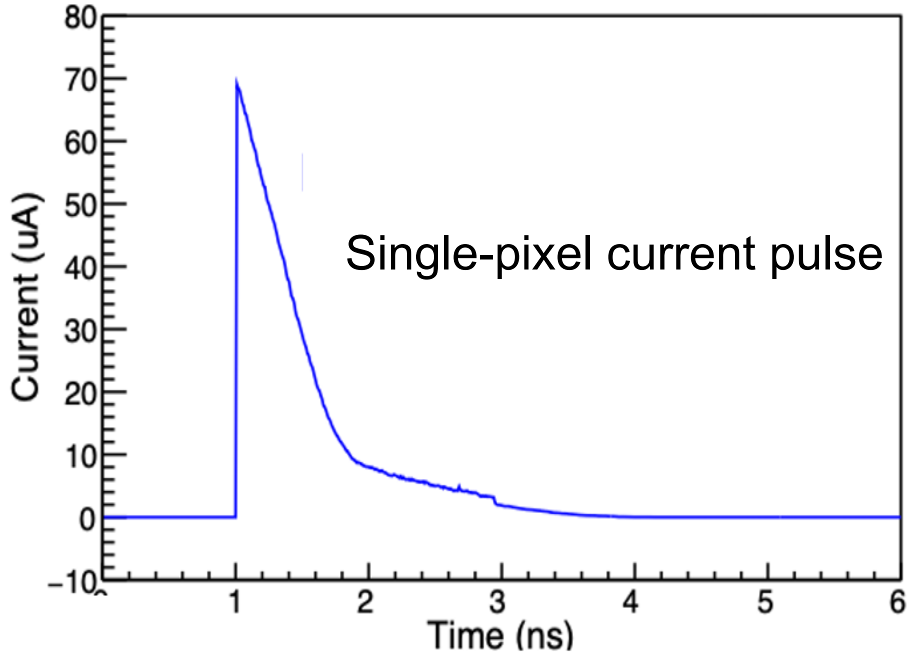
- Position 1: Also suggested by accelerator colleagues
  - Captures differences between inner and outer sides



The Simulation to Estimate the Signal in the Detector

- Types of secondary particles detected
  - Photon-dominated （~87% of detected secondary particles）
  - Electrons < 8%
  - Others ~ 5%
- Detector performance at nominal luminosity （Position3）
  - Total Energy deposition： ~6 MeV per bunch crossing
  - Single-pixel current pulse: ~70 μA, ~3 ns full width

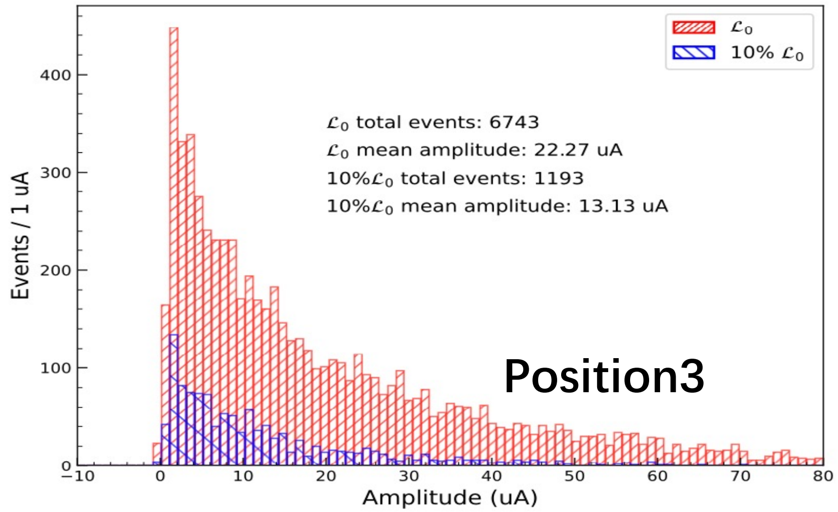


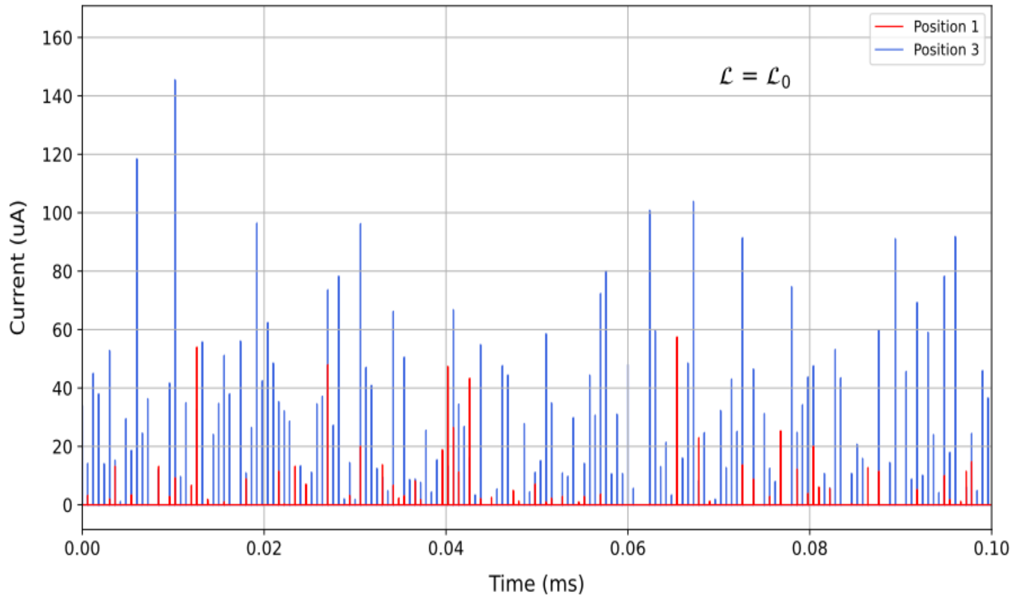


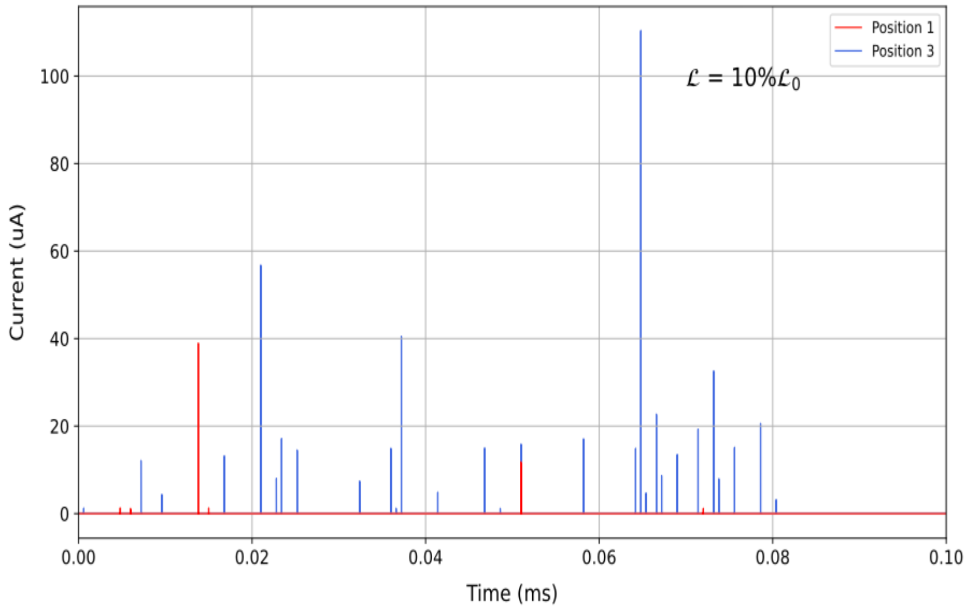
The Simulation to Estimate the Signal in the Detector

- Detector response to luminosity reduction
  - Simulation conditions: $\mathcal{L}_0$ (nominal) vs. $10\%\ \mathcal{L}_0$

- Observed effects at reduced luminosity
  - Fewer signal peaks (events decrease)
  - Lower amplitude per peak (weaker individual signals)





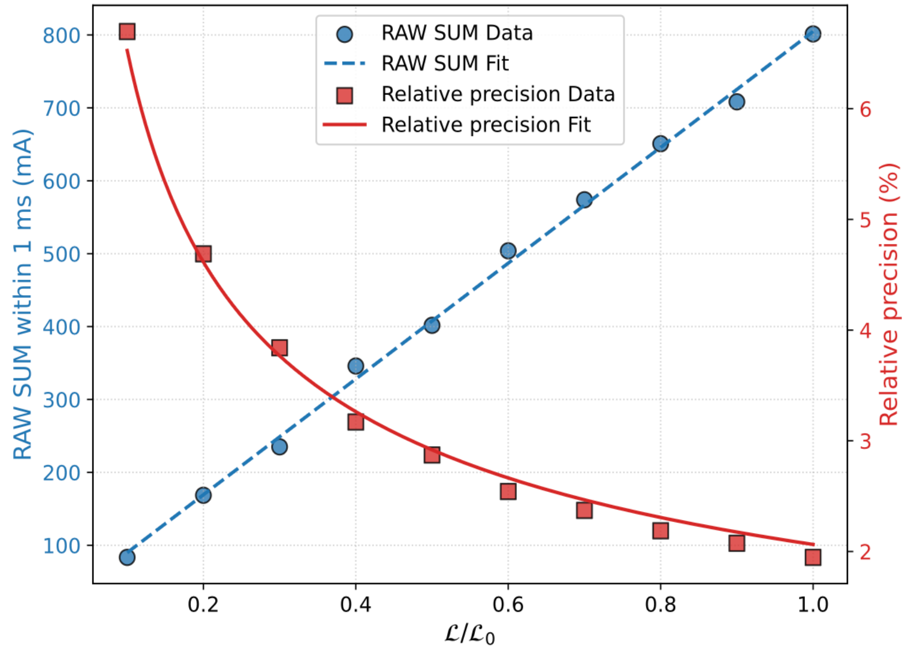


The Simulation to Estimate the Signal in the Detector

- Quantifying Detector Response vs. Luminosity
  - RAW SUM: Sum of sampling points exceeding threshold within 1 ms

$$\text{RAW SUM} = \sum_{s\in\mathcal{S}} \sum_{p\in\mathcal{P}} i_j(s,p) \qquad \text{at Position 3}$$

p: pixel number ; s: sampling point （10GHz, 1ms）



- Key findings
  - Liner relationship: RAW SUM proportional to luminosity
  - Precision: $\nu \propto 1/\sqrt{L}$
    - ➢ Nominal L_0: 2%
    - ➢ 10% L_0: ~7%
  - SuperKEKB experience:

    Even 7% precision feedback reduces beam offsets

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A simulation-based design of the CEPC fast luminosity monitor detector using 4H-SiC

Yanpeng Li,[a,b] Meng Li,[b,c] Xingrui Wang,[a] Qiming Ye,[d] Weimin Song,[a,*] Xiyuan Zhang,[b,*] Congcong Wang,[b] Suyu Xiao,[e] Haoyu Shi,[b] Dou Wang,[b] Philip Bambade[c] and Xin Shi[b]

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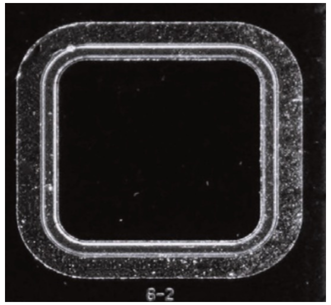
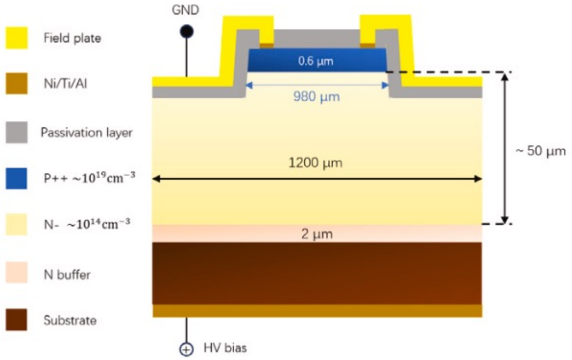
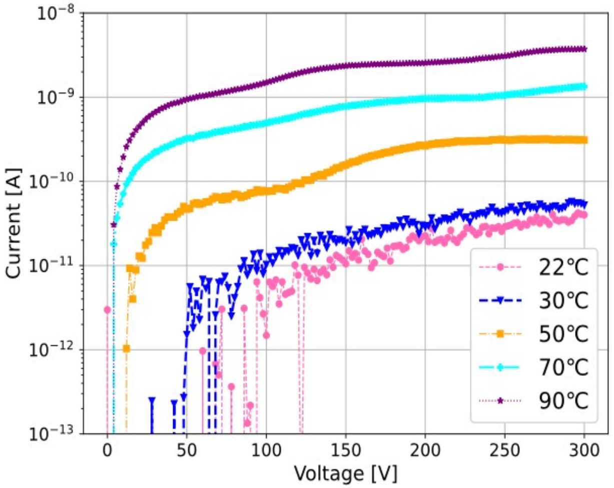
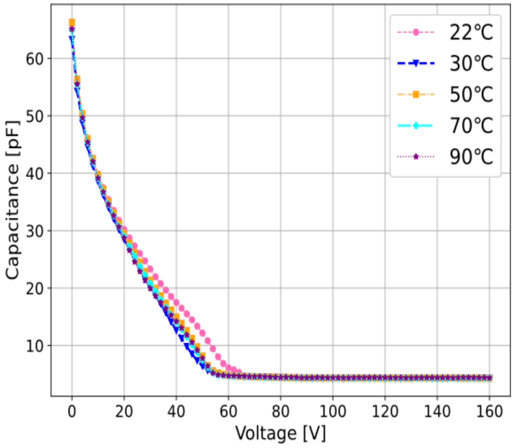
4H-SiC detector development @ IHEP —— SICAR1_PIN detector

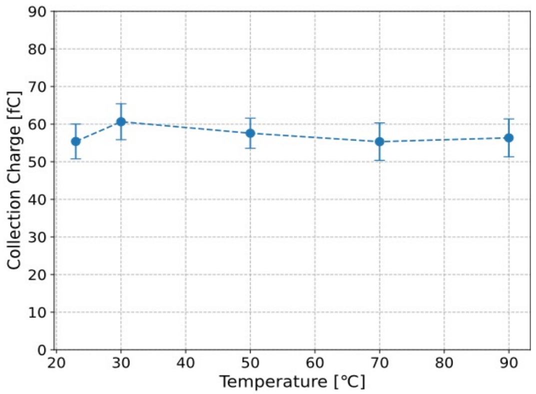
- 4H-SiC PIN detector structure （1.2 x1.2 mm^2）
  - Full epitaxial growth including N- active region(50 μm) and P++ layer
  - Mesa termination + Field plate → reduced field crowding
  - Without high temperature ion implantation and high temperature post-annealing
- Excellent thermal stability
  - Ultra-low leakage current: ~50 pA at RT, ~10 nA at 90°C @300V
  - Capacitance temperature stability
    - ➢ Full depletion voltage ~ 76V
    - ➢ Full depletion capacitance: ~ 3.5 pF
  - CCE （α） ： negligible variation
  - Ultra fast rise time: < 350ps @90°C

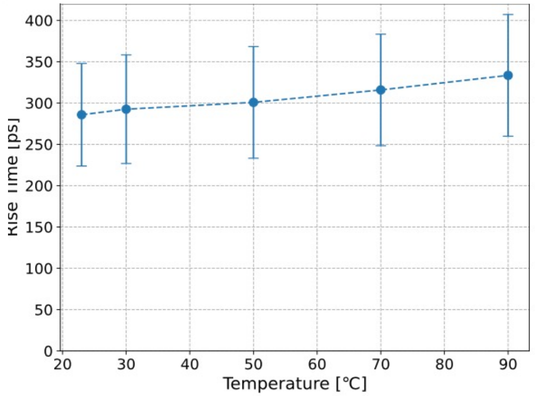








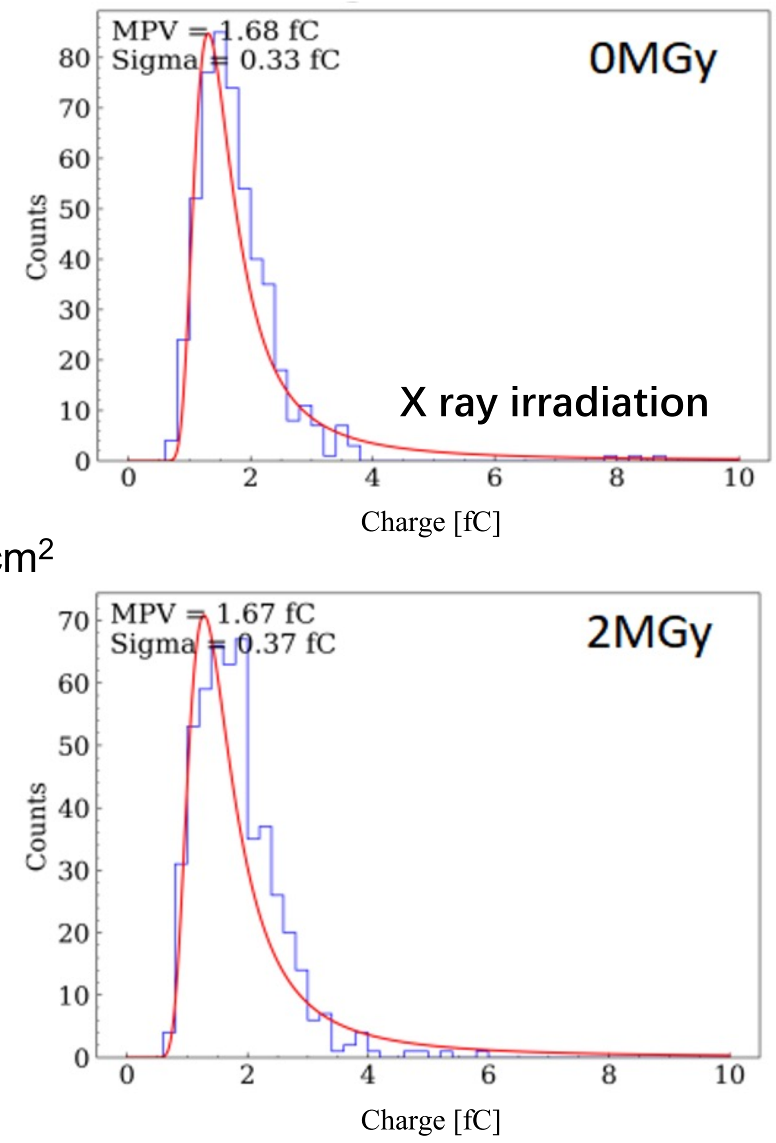


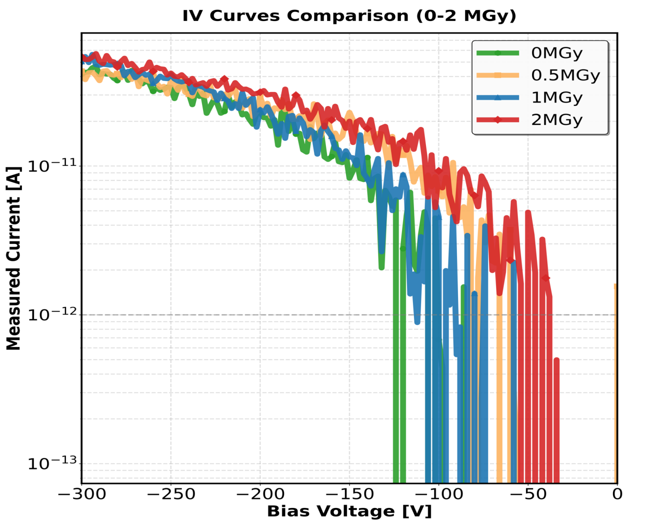


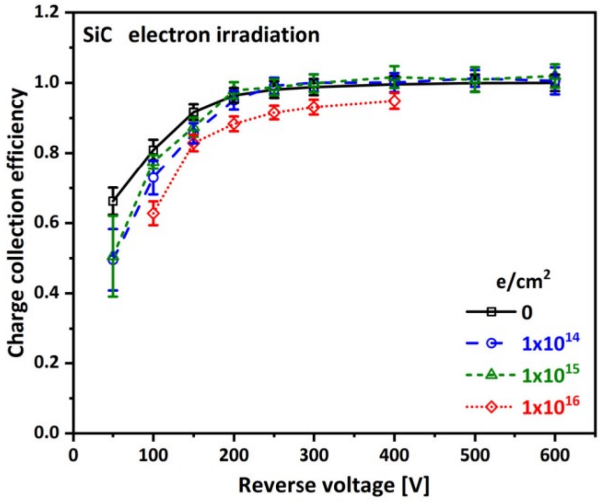
[https://doi.org/10.1016/j.nima.2025.171178]

4H-SiC detector development @ IHEP —— SICAR1_PIN

- FLM for CEPC—Secondary particles fraction
  - γ： 87%； e-： 8%
- X-ray radiation hardness up to 2MGy
  - Leakage current remains stable
  - CCE （β particle） — no degradation
- Electron radiation hardness up to $1x10^{16}$ e/cm^2
  - CCE reduction in the range of 10% at $1x10^{16}$ e/cm^2







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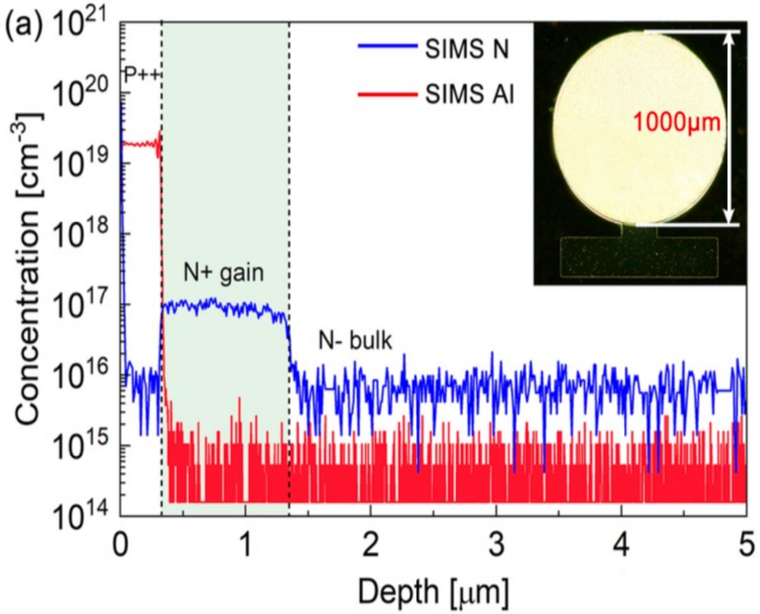
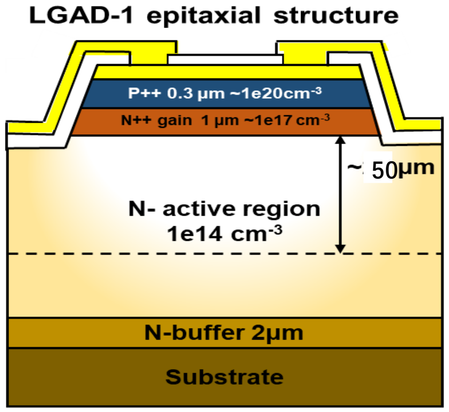
4H-SiC detector development @ IHEP —— SICAR1_LGAD

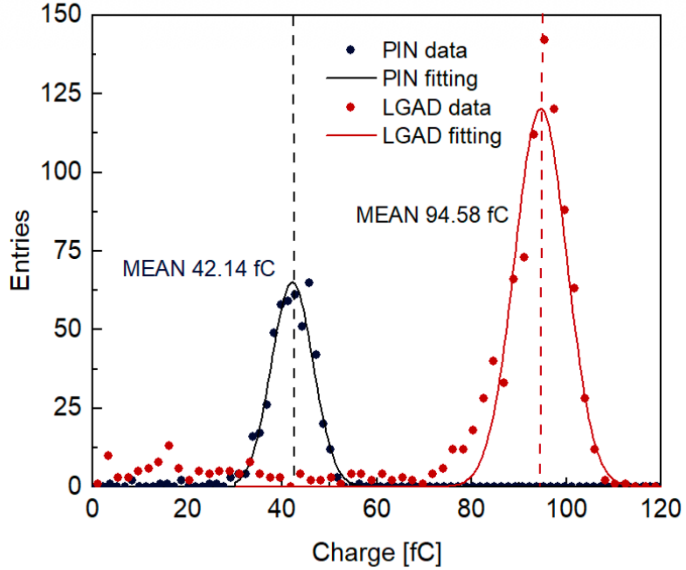
- 4H-SiC LGAD detector structure （1 x1 mm^2）
  - Full epitaxial growth including N- active region(50 μm) N+ gain layer and P++ layer
  - Mesa termination
  - Without high temperature ion implantation and high temperature post-annealing

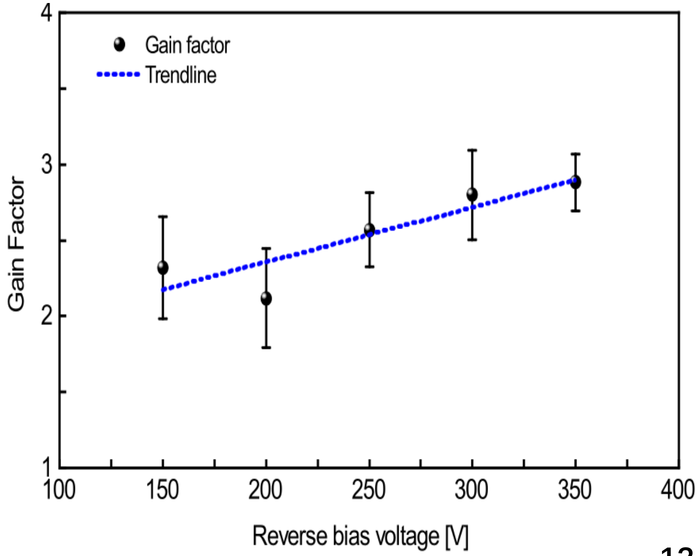




- Gain factor calibration with α source （^{241}Am）
  - Gain factor: 2-3 @ 300V

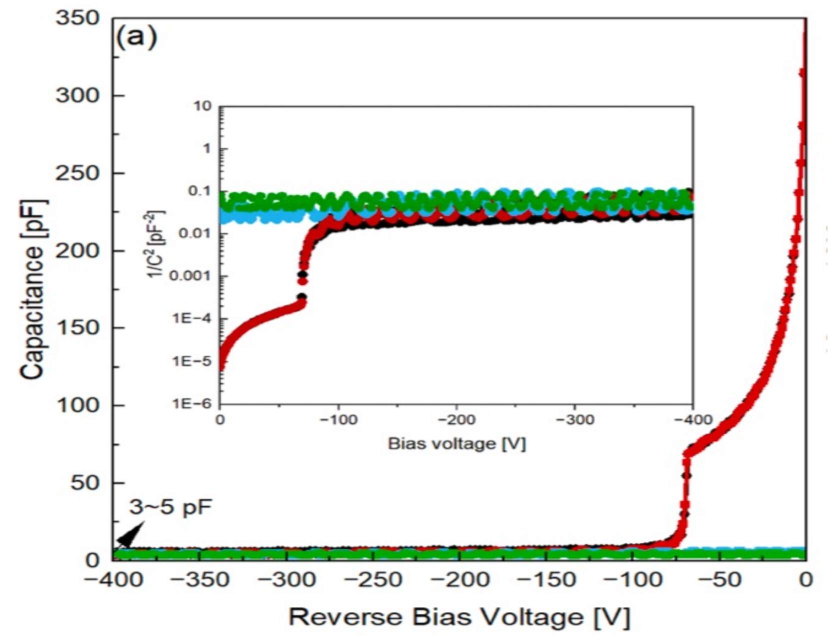
[DOI: 10.1109/TNS.2024.3471863]

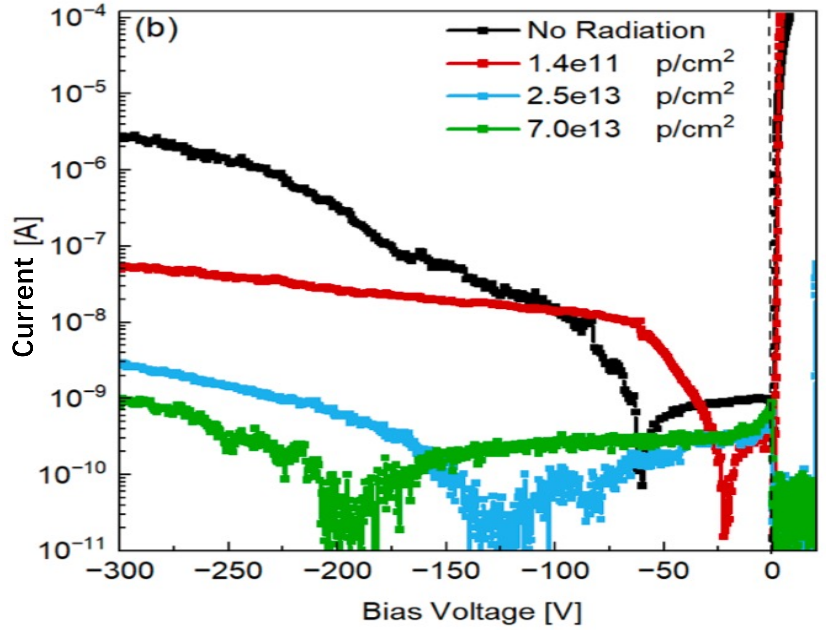




4H-SiC detector development @ IHEP —— SICAR1_LGAD

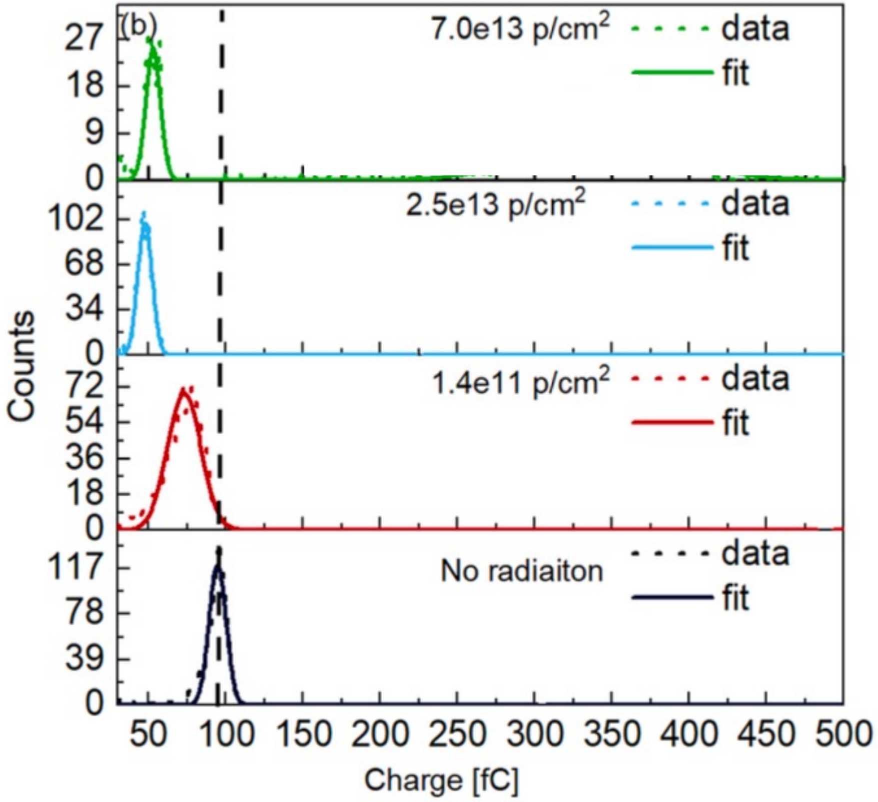
- 4H-SiC LGAD proton irradiation hardness
  - Beam energy: **80 MeV ;**
  - Fluence: 1.4e11p/cm^2 , 2.5e13p /cm^2 , 7.0e13 p/cm^2
  - CV
    - ➢ Parallel-plate capacitor-like (2.5e13 p/cm^2 ~7e13 p/cm^2)
    - ➢ Full depletion capacitance 3-5pF
  - IV
    - ➢ > 1μA @300V (No irradiation);
    - ➢ 5 orders of magnitude higher than PIN
    - ➢ Decreases with increasing fluence; reaches nA level at high fluence

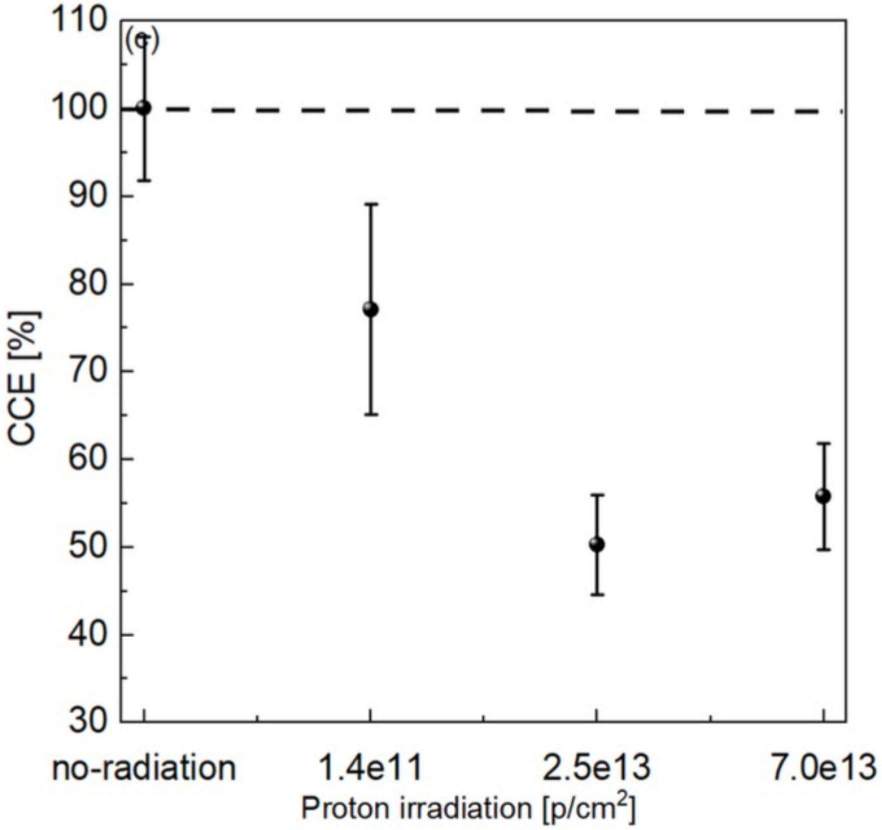




4H-SiC detector development @ IHEP —— SICAR1_LGAD

- Charge collection vs. irradiation fluence
  - CCE degrades with irradiation fluence ↑
  - 7e13p/cm^2 → CCE drops to 57% → Decay to a PIN device（Gain disappeared）



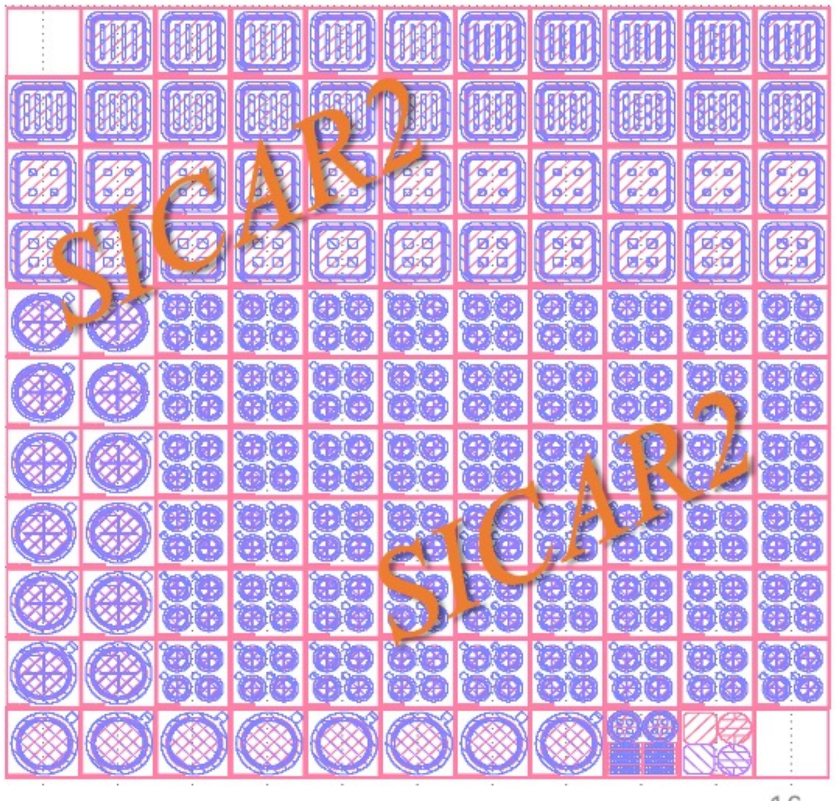


[DOI: 10.1109/TNS.2025.3635073]

4H-SiC detector development @ IHEP —— SICAR2_LGAD

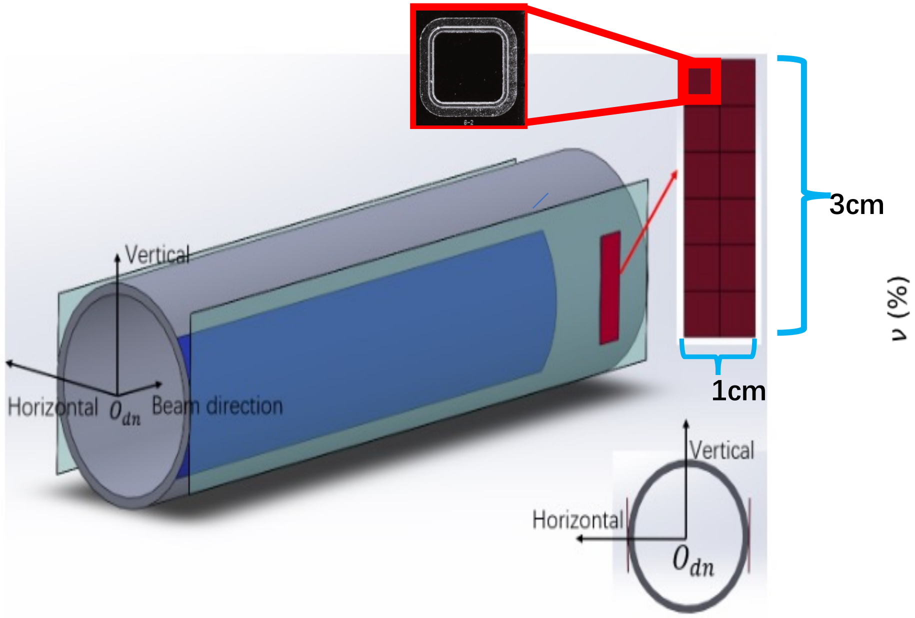
- 4H-SiC LGAD optimization_SiCAR2
  - Adjust the concentration of gain layer → Objective: gain factor > 10 @ 300V
- **Transitioning SICAR2_LGAD to a 350nm MOSFET Process Platform**
  - Replacing Contact with Stepper Lithography
  - Single Reticle Field: 2.2cm × 2.2cm
  - Die size: 1.5mm ×1.5mm & 0.6mm × 0.6mm
  - Mesa termination with field plate to prevent the early breakdown

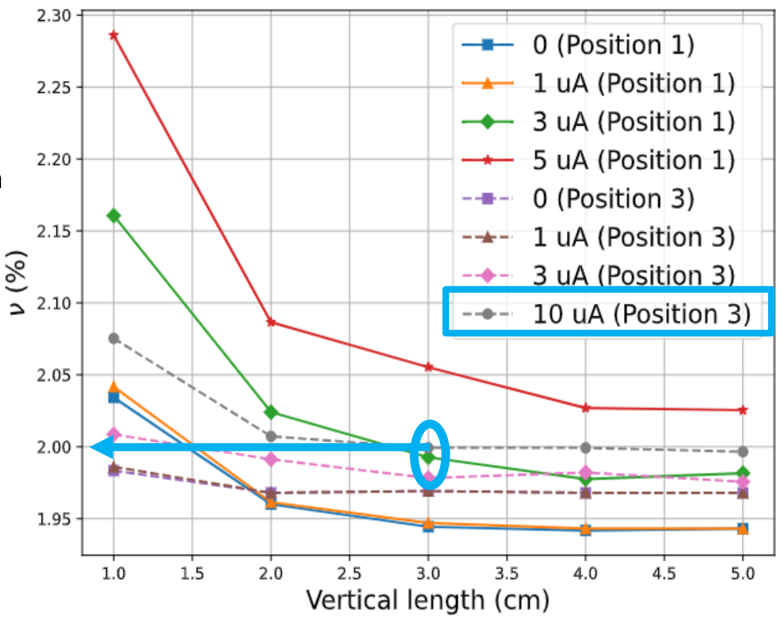
Undergoing……



Summary

- Simulation determines the optimal position and geometry of the SiC-based Fast Luminosity Monitor for CEPC，meeting the 2% precision requirement.
- Simulated detector response shows a linear relationship with luminosity, proving its capability for real-time luminosity feedback.
- The optimized SiC LGAD designed, now in fabrication; delivery expected by summer.





Thanks!

Back up

- 4H-SiC LGAD optimization_SiCAR3
  - High-temperature (500°C); high-energy implantation > 1 MV
  - High-temperature annealing (1700°C) → Activate carriers and repair defects
  - High fabrication complexity and high cost → MPW

Undergoing……