CEPC Fast Luminosity Detector design using SiC

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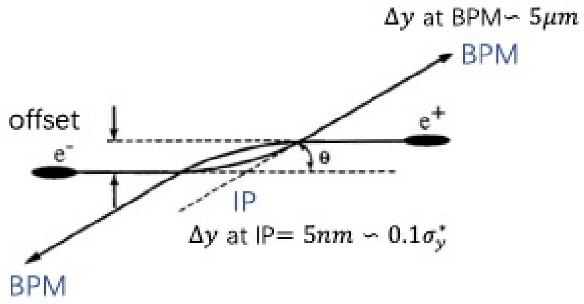
Necessity of the Fast Luminosity Monitor for CEPC

- Nano-beam 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

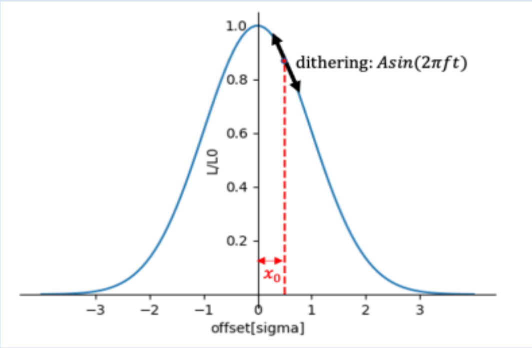
Vertical IP orbit feedback——**Beam-beam deflection driven method**

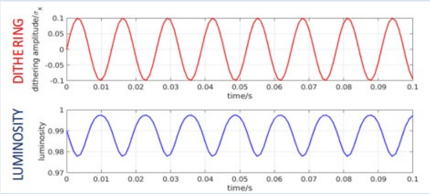


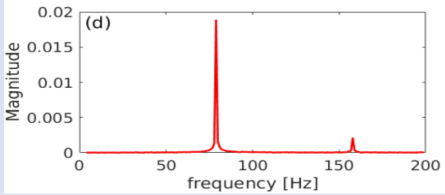
$\Delta y'_{\pm} = -\frac{r_e N_{\mp}}{\gamma_{\pm}\sigma^*_{y\mp}(\bar{\sigma}^*_{x\mp}+\sigma^*_{y\mp})}\Delta y_{IP}$ $\Delta \mathbf{y}_{\mathbf{BPM}} = \sqrt{\boldsymbol{\beta}^*\boldsymbol{\beta}_{\mathbf{BPM}}}\Delta \mathbf{y}'$

Based on the measurement of the offset with BPMs upstream and downstream of the IP

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







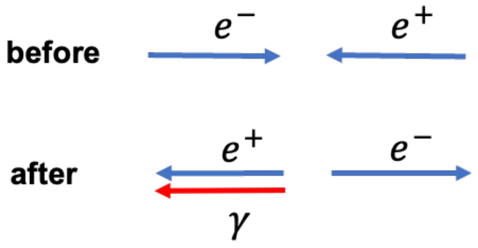
Based on the measurements of the luminosity with a certain frequency dithering

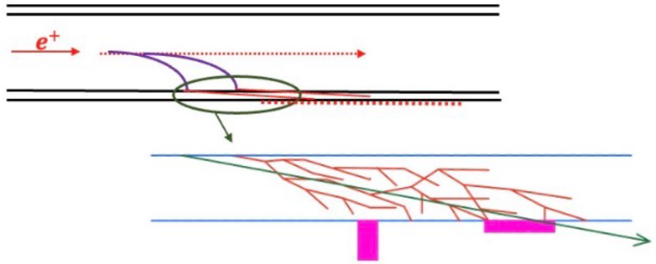
- Fast luminosity monitor: considering the weak beam-beam deflection and at a lower required feedback speed (1kHz)

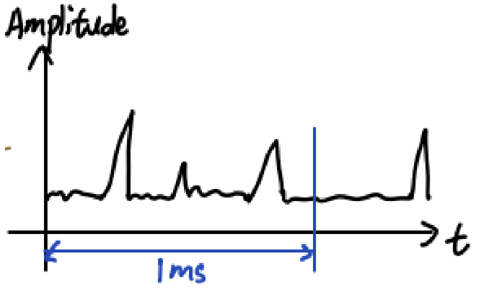
Fast Luminosity Monitor working principle

Meng Li

- 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)

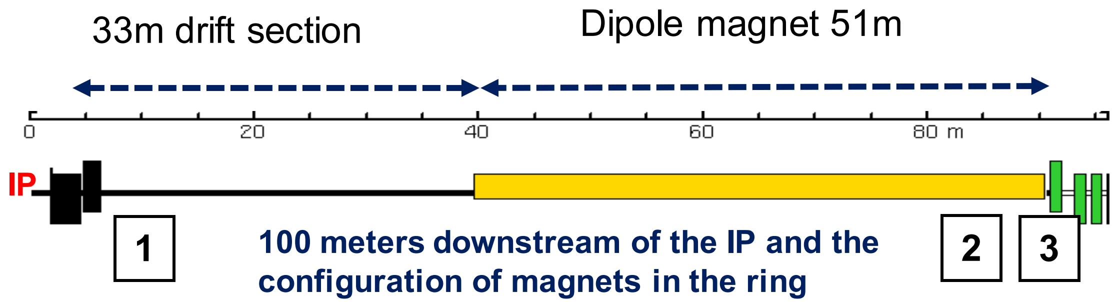
Luminosity	Cross section	Number of Bhabha	Aimed precision	Required fraction
5×10^{34}	0.127 barn	6.35×10^{6} in 1ms	2% in 1ms	4×10^{-4}

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

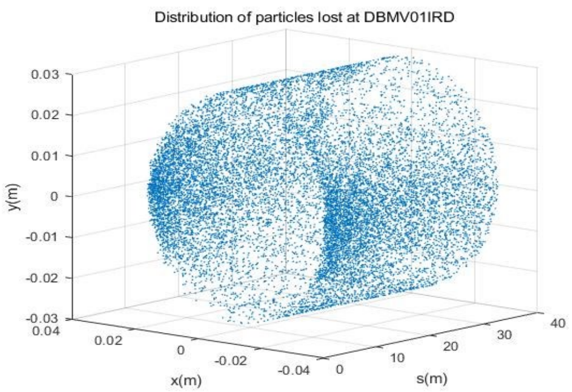
The position of Fast Luminosity Monitor

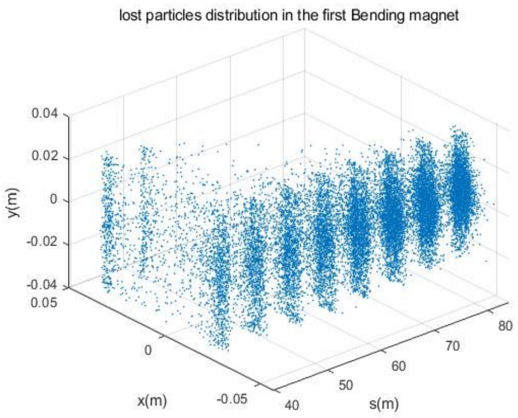
Meng Li

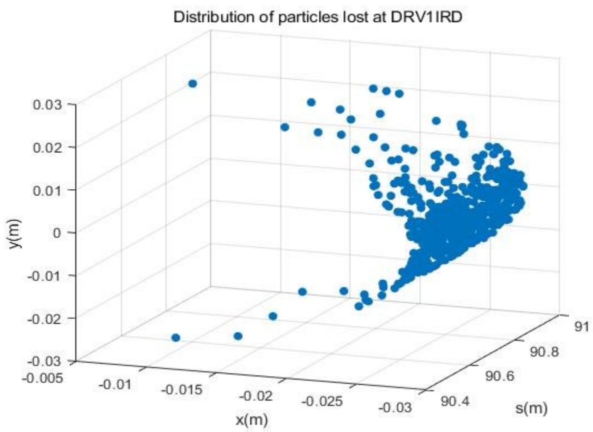
- The low-energy scattered electrons from the IP first go through three quadrupole magnets, 33m drift section, 51m bending magnet…
- The scattered Bhabha electrons most get lost after the three quadrupoles and on the first dipole magnet
- Drift section behind the dipole magnet is shorter, the number of lost in this section is relatively low.



100 meters downstream of the IP and the configuration of magnets in the ring







- Three potential locations were considered: before, inside, and after the first bending magnet

The position of Fast Luminosity Monitor

Meng Li

	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	355ns		
Detector technology possibility	LGAD, SiC, Diamond		

References

[1] IP luminosity feedback and preliminary design considerations for luminosity monitoring at CEPC

[2] Meng Li et al., “Preliminary design consideration for CEPC fast luminosity feedback system”, Radiation Detection Technology and Methods, 2024. doi: 10.1007/s41605-024-00491-8

[3] D. El Khechen et al., “First beam loss measurements in the SuperKEKB positron ring using the fast luminosity monitor diamond sensors” , Physical Review Accelerators and Beams, 2019. doi.org/10.1103/PhysRevAccelBeams.22.062801

[4] C. Pang et al., “A fast luminosity monitor based on diamond detectors for the SuperKEKB collider”, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2019. DOI:10.1016/J.NIMA.2019.03.071

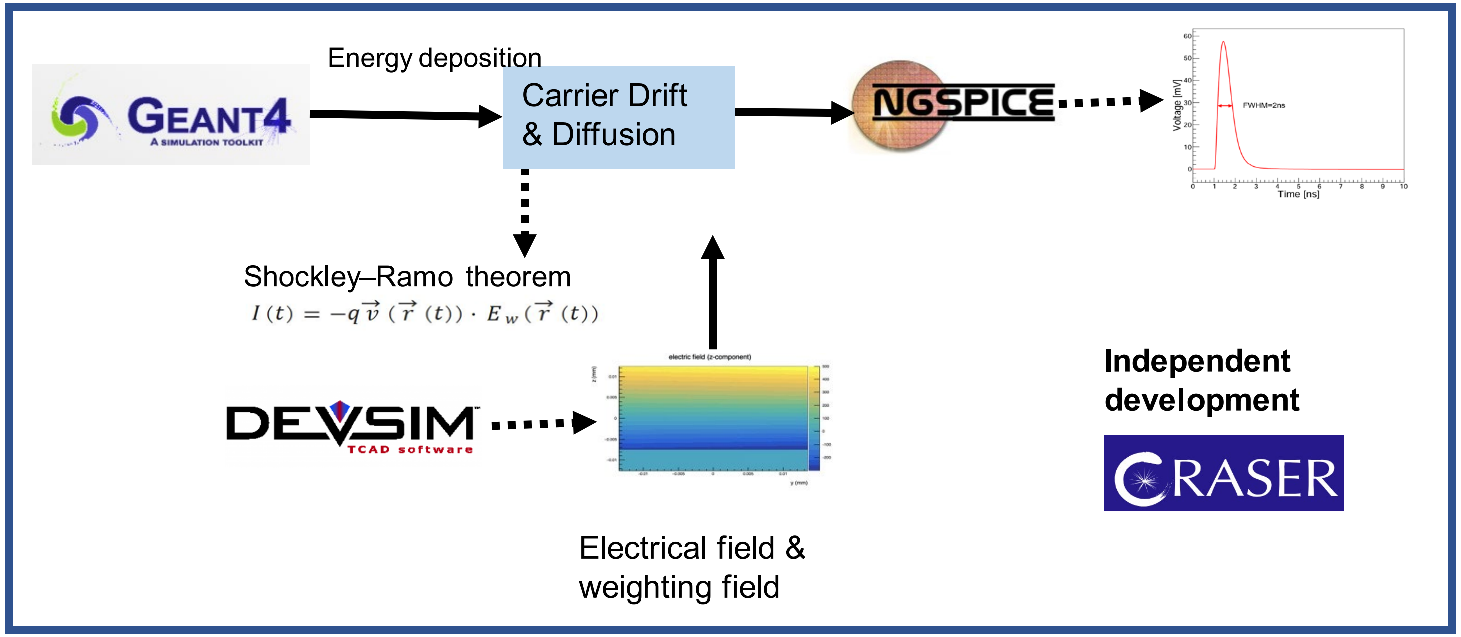
[5] https://theses.hal.science/tel-01522803v1/document

[6] https://theses.hal.science/tel-03092297v1/document

The Simulation to Estimate the Signal in the Detector

- Simulation workflow in RASER (**RAdiation SEmiconductoR)**
  - The energy deposition of Bhabha electron events from GEANT4
  - Electrical field & weighting field from DEVSIM
  - Current signal from Calcurrent in RASER (RAdiation SEmiconductoR)
  - Voltage signal from NGSPICE

https://raser.team

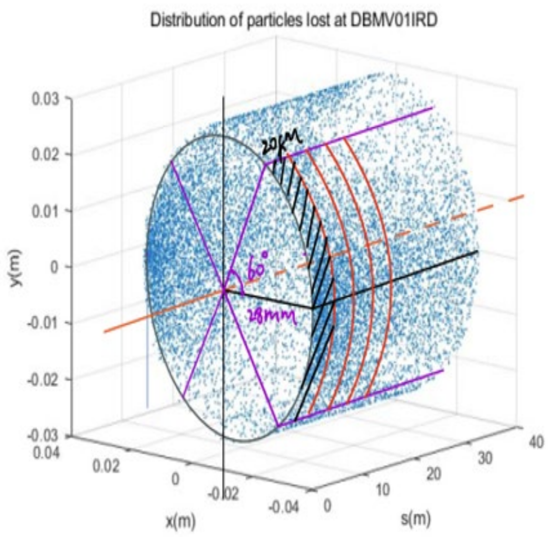


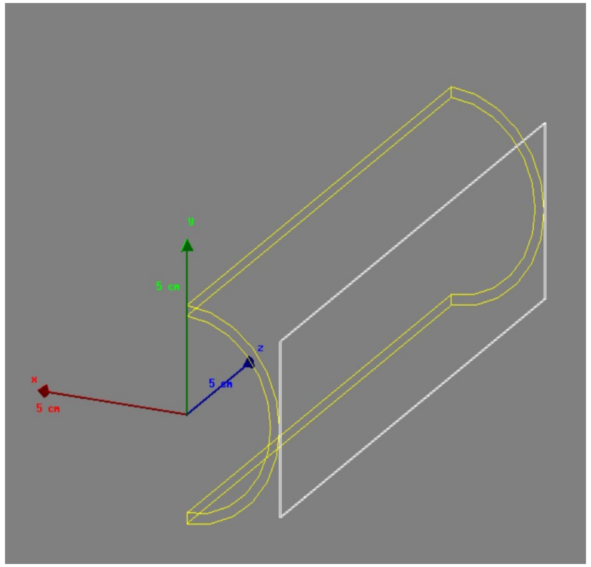
Advantages

- ◆ Open Source;
- ◆ Strong expandability;
- ◆ Easily interact with other software

The Simulation to Estimate the Signal in the Detector

- Structure of beam pipe and detector in GEANT4
  - The dimensions of the detection area of position1 (5cm*20cm) selected as an example
  - A plane instead of a barrel shape detector tangent to the beam pipe





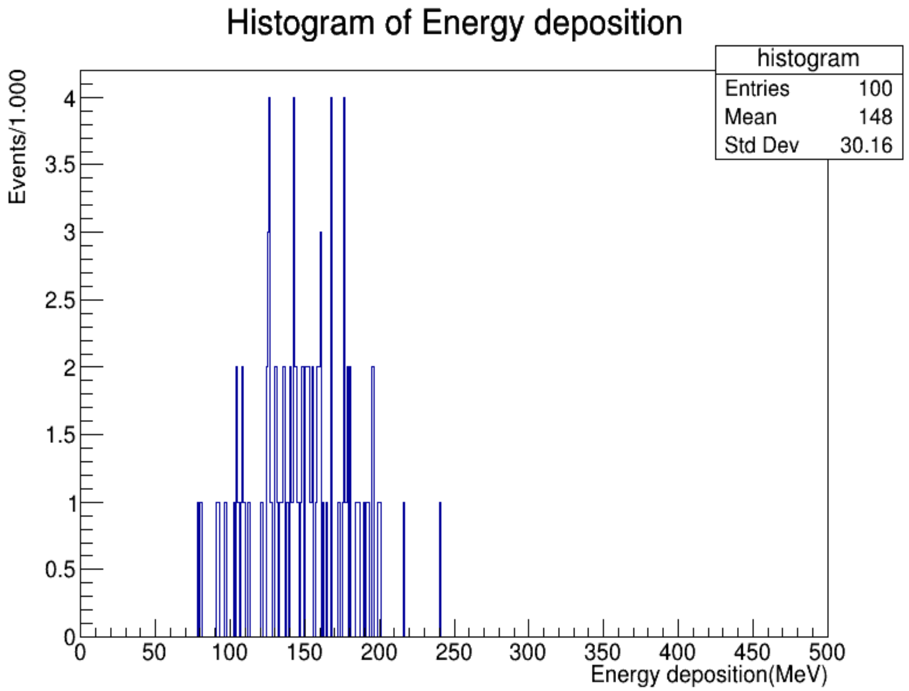
The specific Bhabha electron position information

- Initial position:[-26.9mm(X), 0(Y), -100mm(Z)]
- Final position:[-28mm(X), 0(Y), 10mm(Z)]
- Momentum direction:[-0.01mm(X), 0(Y), 1(Z)]

- A Bhabha electron hitting the beam pipe in a specific direction and collect information of secondary particles

The Simulation to Estimate the Signal in the Detector

- The Energy deposition of one Bhabha electron event
  - 100 events of Bhabha electron hits on the beam pipe at the same position
  - The mean value of **energy deposition** from single Bhabha electron is 148 MeV
  - Tracking the distribution of more Bhabha electrons to reflect the actual situation

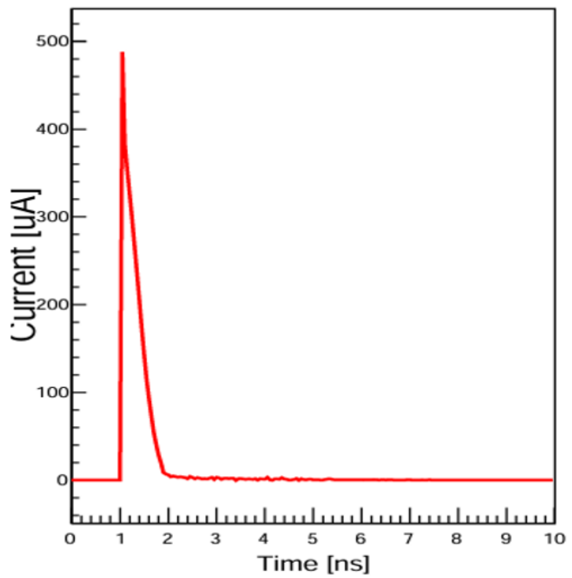


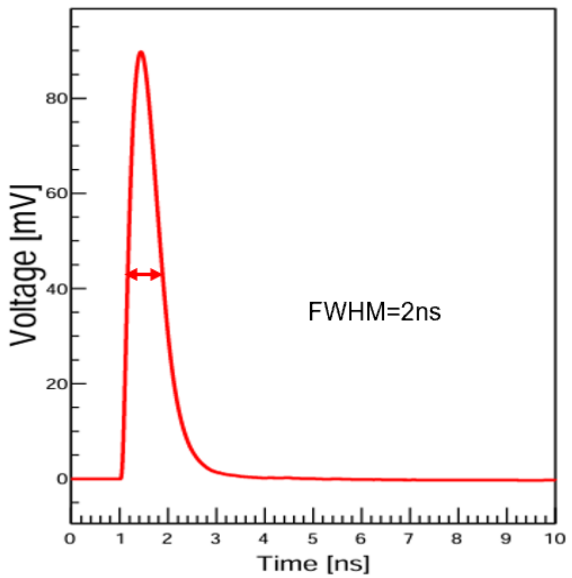
- Types and proportions of secondary particles
  - Most secondary particles generated are photons

Secondary particle type	Number(rate)
γ	912（81.07%)
e-	119（10.58%)
e+	75（6.67%)
other	19 （1.69%)
total	1125（100%)

The Simulation to Estimate the Signal in the Detector

- The current response output from RASER
  - The weighting field and electric field of the SiC PIN detector output from DEVSIM
  - The Energy deposition of the secondary particles output from GEANT4
  - Shockley-Ramo theorem $I(t) = -q\vec{v}(\vec{r}(t)) \cdot E_w(\vec{r}(t))$



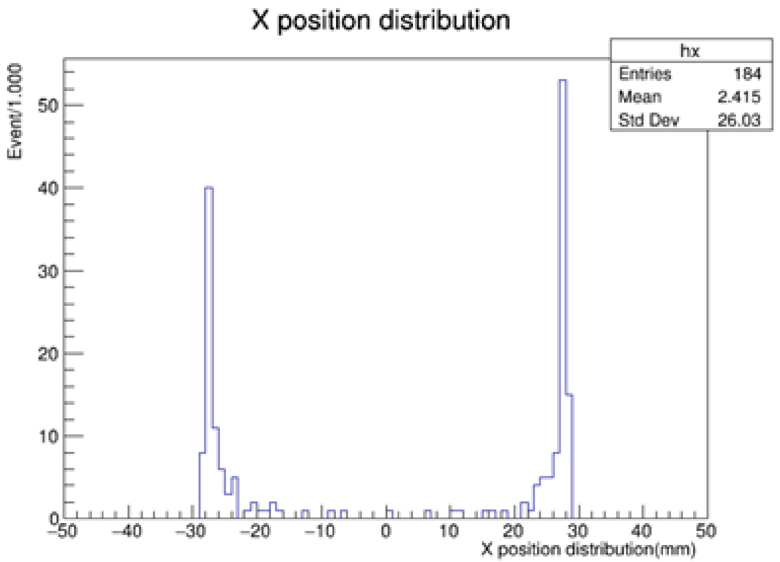


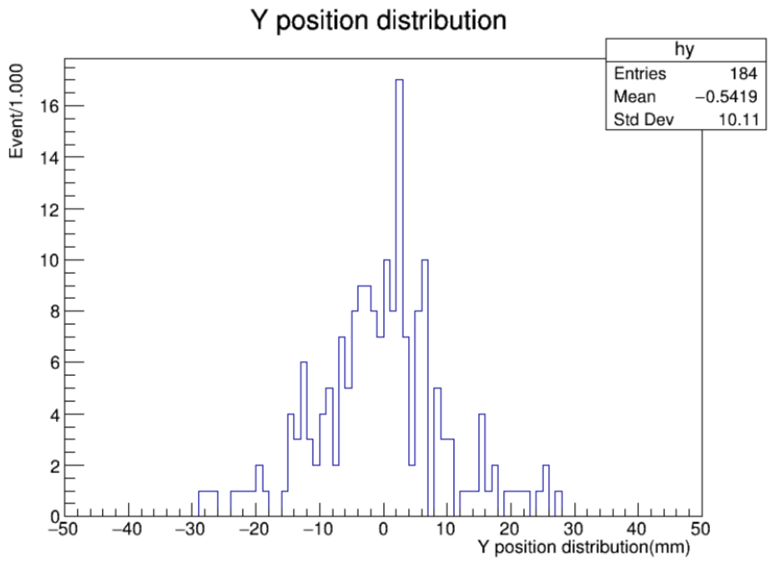
- The voltage response output
  - A specific Bhabha electron hitting the beam pipe produces a voltage value of 90mV (Amplifier 20dB)
  - Ignore the readout electrical noise(1mV), no fluctuation of the waveform
  - The resolution(FWHM) is 2ns

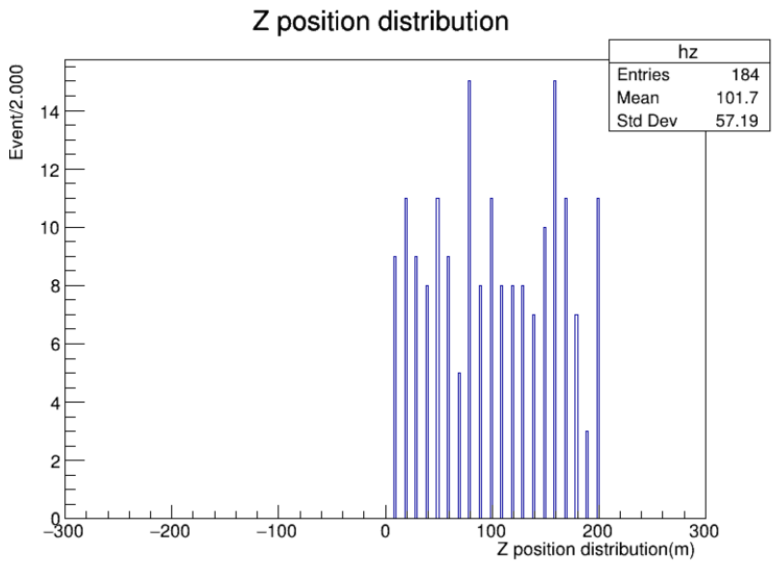
The Simulation to Estimate the Signal in the Detector

Datafile provided by Meng Li

- Generating the Bhabha particles through the program BBBREM
  - Tracking scattered positrons up to 100 meters downstream of the IP using the SAD code and calculating the loss map
  - 100000 Bhabha electrons loss in the beam pipe
- Filter the Bhabha electrons hitting the position of $S \in (10, 10.2)$ on the beam pipe
  - The number of events filtered is 184
  - The number of the events hitting on both sides (X axis) of the beam pipe is not perfect symmetrical
  - Considering the Bhabha scattering on one side (on X axis)







The Simulation to Estimate the Signal in the Detector

- The loss map of the Bhabha electrons only shows the position information at the beam pipe without the hitting time
- In Geant4, the geometry, material, etc. are generally treated as a fixed, static background. Time information can't be processed in GEANT4

	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	$1.7 \times 10^{-4} rad$	$7 \times 10^{-4} rad$	$7 \times 10^{-4} rad$
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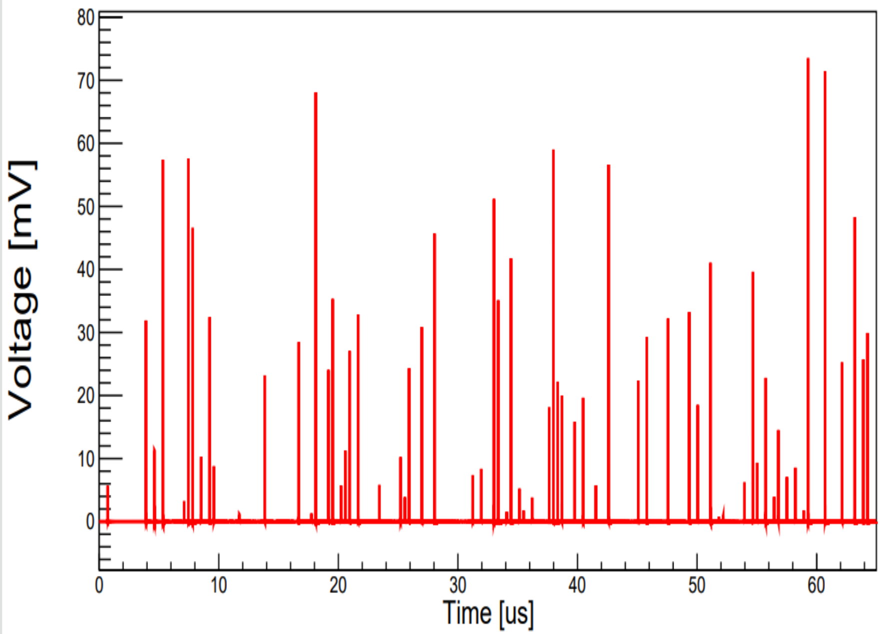
Backgrounds	SR Photons in 1 Side	-	-
Beam-Beam Deflection Impact	sensitive	less sensitive	less sensitive
Detector Number	2	1	1
Detector Measurement Parameters	Number of signals within 1ms		
Detector Time Resolution	355ns		
Detector technology possibility	LGAD, SiC, Diamond		

How to process Hitting time?

- The average number of Bhabha electron hitting the beam pipe per collision are 3.4 at two sides
  - Considering one Bhabha electron on one side at one collision
  - Based on a Poisson probability distribution with mean 1.7 and combine the resulting secondaries for the signal calculation (next step)
- The time interval between bunch and bunch is 355ns
- The timestamp to the current generated by each Bhabha electron added in RASER, with a time interval of 355ns

The Simulation to Estimate the Signal in the Detector

- The voltage signal of Bhabha electron events within 65μs
  - The amplitude larger than 10mV accounts for 80% of the total signal



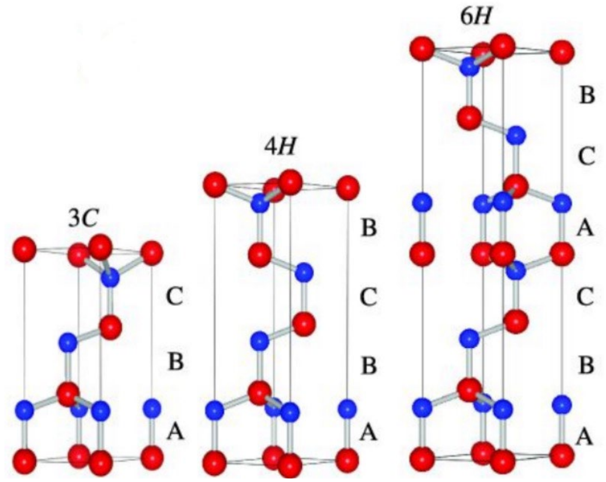
  - Increase the voltage signal → Development of the SiC LGAD
  - Reduce the noise → Optimize the electrical readout
- Next Step
  - Optimize the detection area as a detector array and adjust the distribution and position
  - Assumption on the noise in the simulation

Introduction of Silicon carbide detectors

- Pros:
  - Bandgap between silicon and diamond
  - Higher saturation velocity and breakdown field
  - Larger atomic displacement threshold
    → Potentially good radiation resistance
  - No dark current increase after irradiation
  - High thermal conductivity
    → No cooling needs
  - No sensitivity to visible light

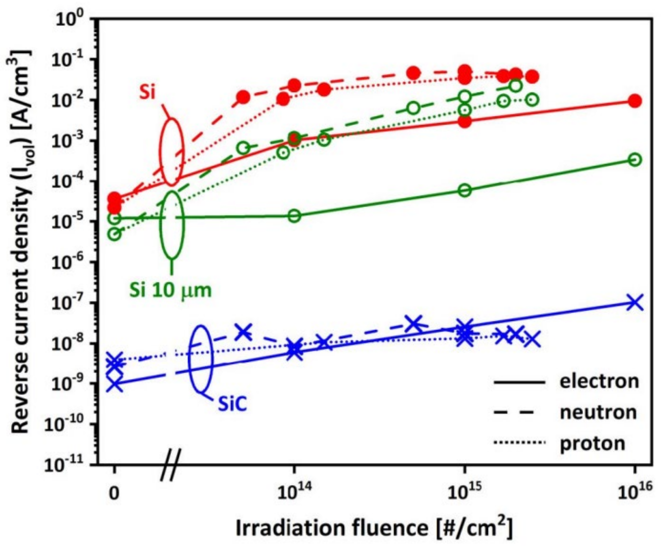
- Cons:
  - Different polytypes(3C, 4H, 6H)
  - Anisotropy
  - Higher ionization energy
    → Smaller signals
  - Epitaxial-grown limited to ~150μm thickness

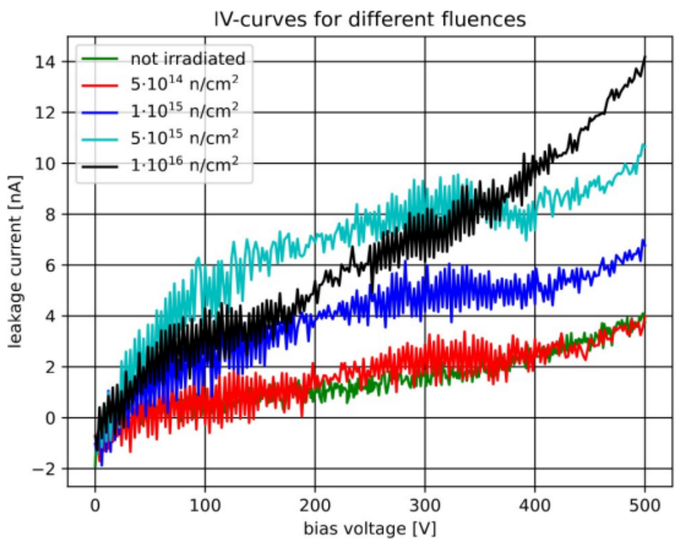
	Silicon	4H-Silicon carbide	CVD Diamond
Band gap [eV]	1.1	3.26	5.5
Ionization energy [eV]	3.6	5 – 8	12.86
atomic displacement threshold	13-20 eV	20-35	43
Density [g/cm^3]	2.33	3.22	3.52
Electron Mobility [cm^2/Vs]	1430	⊥ c: 800; ∥ c: 900	1800-2200
Hole Mobility [cm^2/Vs]	480	115	1200-1600
Saturation electron velocity [10^7 cm/s]	1	2.2	2.7
Breakdown Field [MV/cm]	0.5	⊥ c: 4.0; ∥ c: 3.0	10
e/h pairs per μm	72	57	36

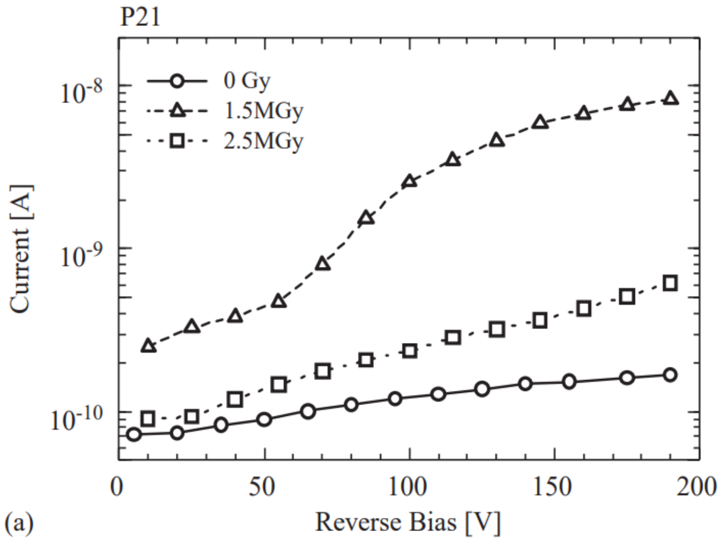


Introduction of Silicon carbide detectors

- Potentially Radiation resistance
  - Leakage current 4-5 orders of magnitude lower than Si[1]
  - No obvious current increase after electron/neuron/proton irradiation up to $10^{16} n_{eq}/cm^2$[1][2]
  - The tolerance of gamma doses up to 2.5 Mgy[3]



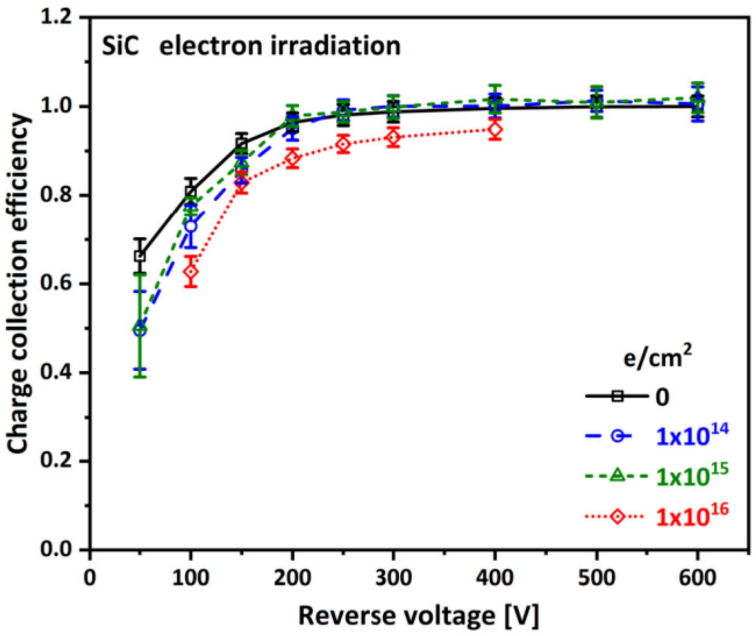


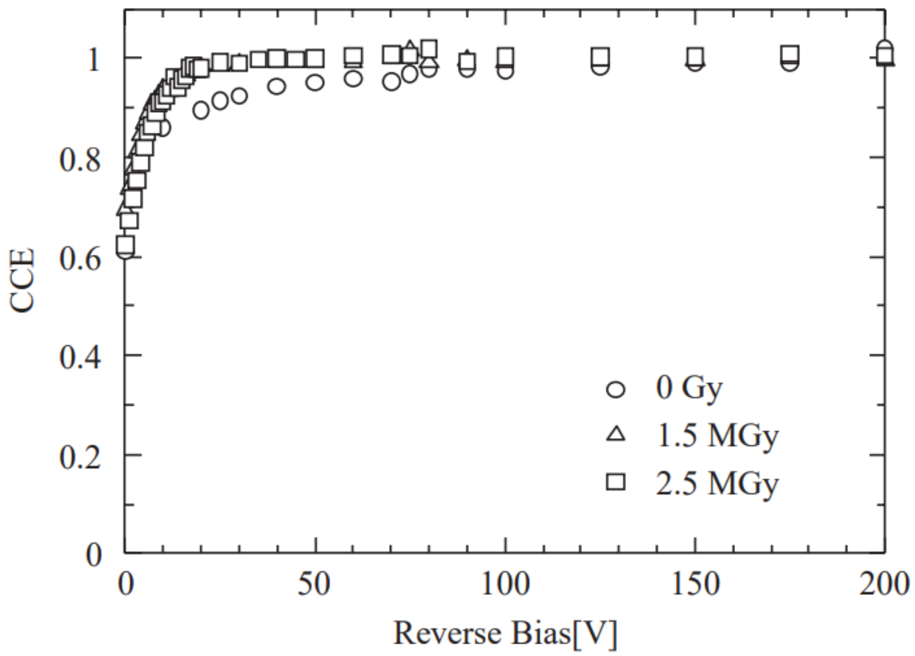


References
[1] Michael Moll et al., Electron, Neutron, and Proton Irradiation Effects on SiC Radiation Detectors, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, 2020.
[2] 41st RD50 Workshop on Radiation Hard Semiconductor Devices for Very High Luminosity Colliders (Sevilla, Spain): Silicon Carbide LGAD RD50 common project.
[3] Akimasa Kinoshita et al., Radiation effect on pn-SiC diode as a detector, Nuclear Instruments and Methods in Physics Research A, 2005.

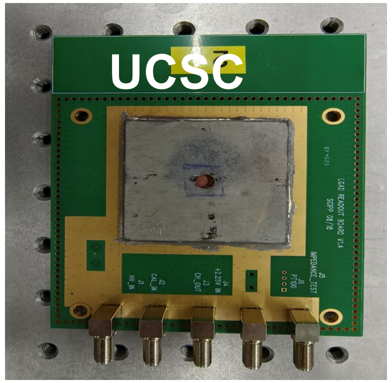
Introduction of Silicon carbide detectors

- Potentially Radiation resistance
  - For electron radiation, the alpha charge collection efficiency (CCE) in reduction of 10% after the highest fluence $10^{16} n_{eq}/cm^2$ [1]
  - For neuron/proton irradiation up to $10^{16} n_{eq}/cm^2$, workable but in reduction of ~80% [1]
  - No obvious affected after gamma doses up to 2.5 Mgy[3]



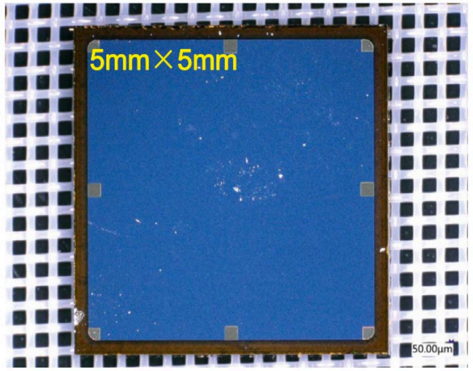


- SiC PIN detector designed in cooperation with NJU
  - Time resolution of PIN detector ~94ps
  - The readout electronics is UCSC single board with amplifier PE1513(20dB)



magnification is 10 times

A



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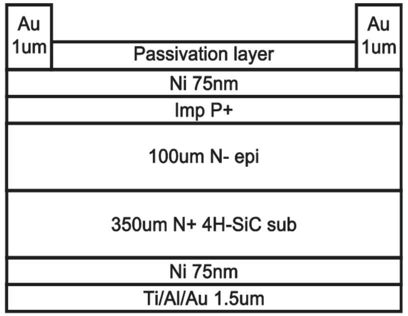
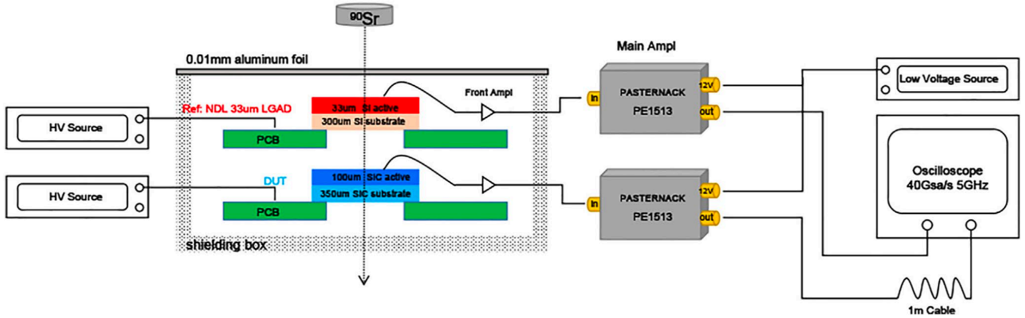
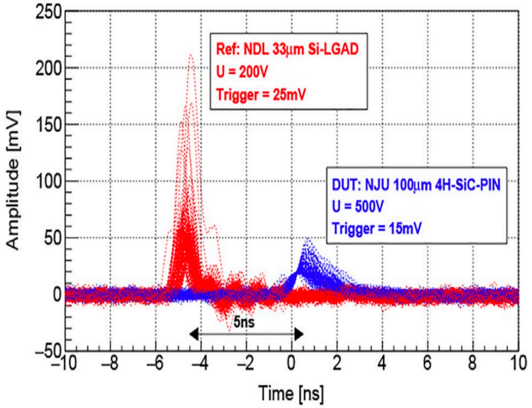
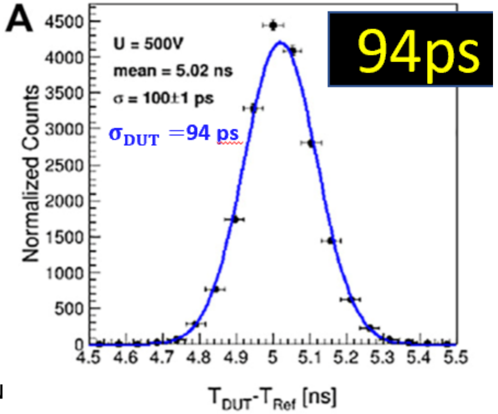


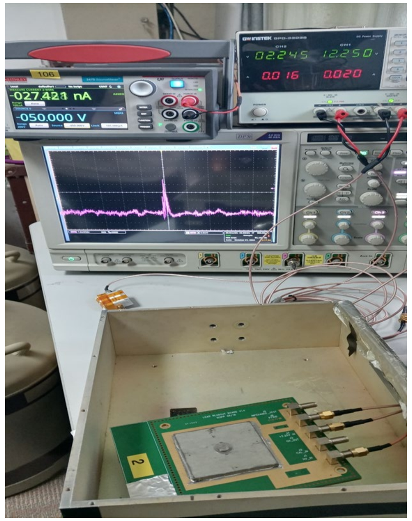




Waveforms from the LGAD (Ref) and 4H-SiC PIN



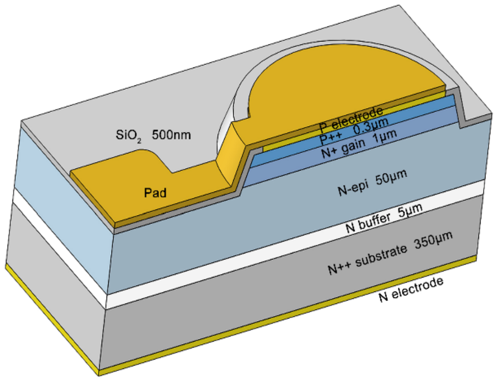
Time resolution <100ps

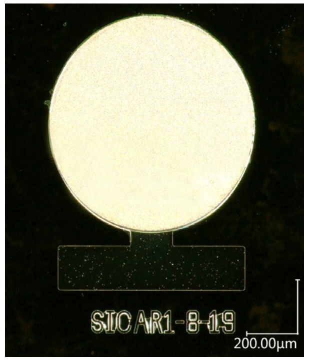


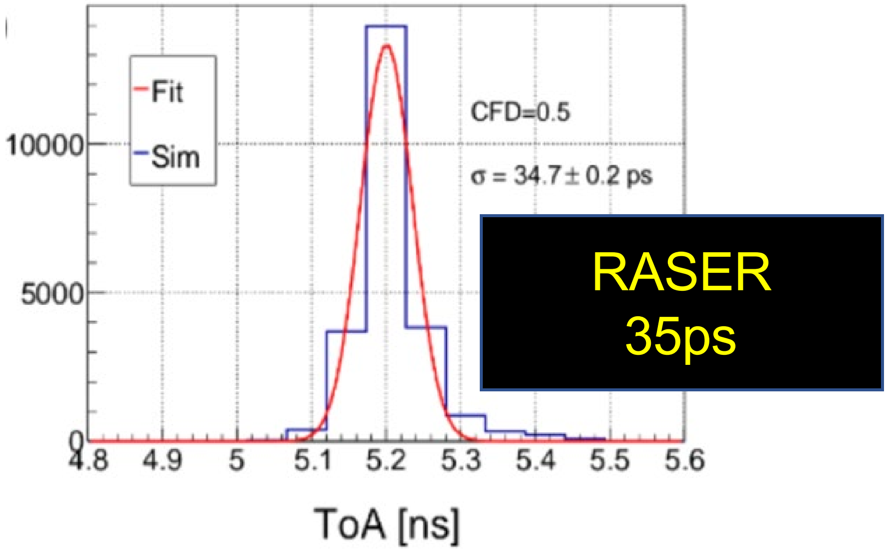
High voltage source (keithley 2470)
Low voltage source (GPD-3303SGWINSTE)
Oscilloscope (DPO-7354C, Tekronix10GHz)

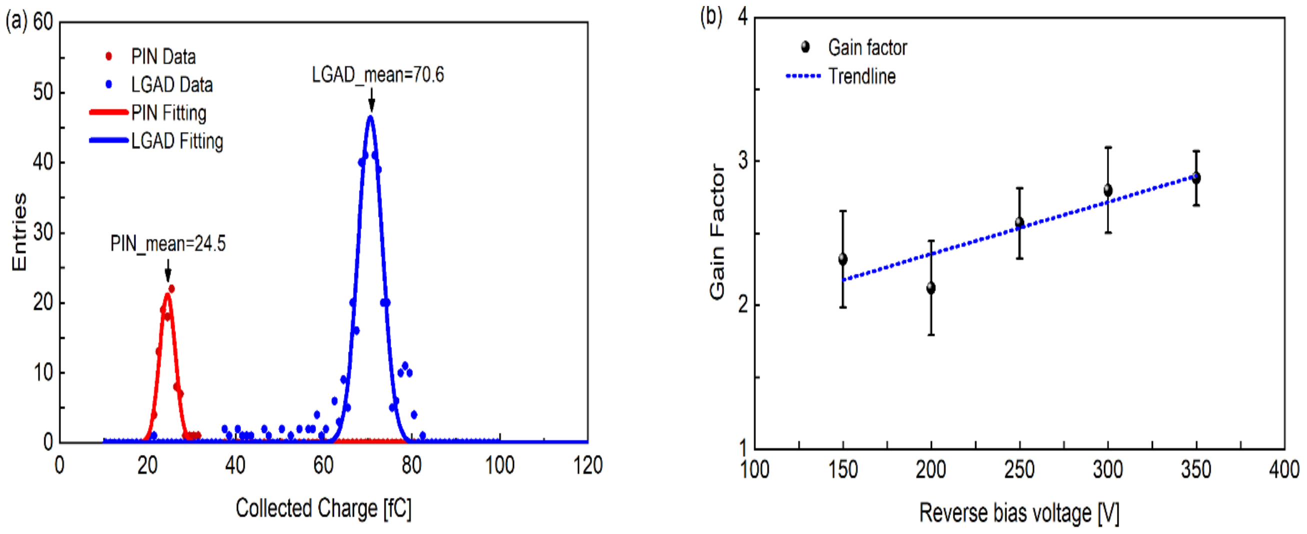
Introduction of Silicon carbide detectors

- 4H-SiC LGAD under development…
  - Independent development of SiC LGAD
  - Simulation of the time resolution of 35ps
  - Charge collection of LGAD 2-3 times bigger than PIN









α particles Charge collection

References
[1] https://doi.org/10.1016/j.nima.2023.168677
[2]https://link.springer.com/article/10.1007/s41605-023-00431-y
[3] Charge Collection Performance of 4H-SiC LGAD (arxiv.org)

Conclusions

- RASER can be used to simulate the voltage response of the SiC detector to the bhabha scattering
- A Bhabha electron hitting the beam pipe produces the voltage response of which the amplitude larger than 10mV accounts for 80% of the total signal and the resolution (FWHM) is 2ns
- Assumption on the noise in the simulation should be considered
- The voltage signals generated by bhabha electrons scattering at different time can be obtained by simulation
- Optimize the detection area as a detector array and adjust the distribution and position to simulate the Bhabha scattering in next step

Thanks!

Backup

SiC sensors for MIP detectors at COMET muon experiment @ J-PARC (Japan Proton Accelerator Research Complex)

- PN diodes in wafer process, 5 mm x 5 mm simple diode
- Reverse bias tolerance of 3 kV
- 50 um epi grown on -(0001) 4H-SiC n-type substrate
- Nd-Na: 4.7 x -10^{14} cm^{-3}
- Thickness: 350 um
- 260 dies with 5 x 5 mm^2 from 4-inch wafer, 4 x 4 mm^2 active area