Simulation Study for CEPC Fast Luminosity Detector based on 4H-SiC

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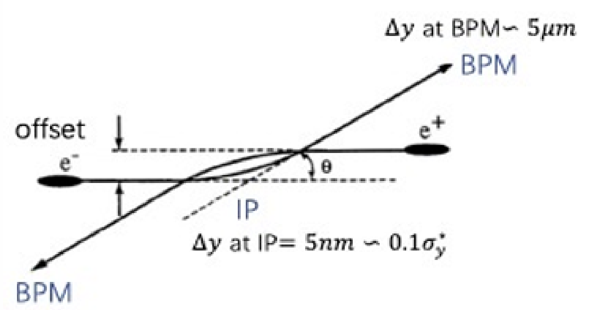
OUTLINE

- Description for CEPC Fast Luminosity Monitor System
- Introduction for 4H-SiC detector
- Simulation Discussion for CEPC Fast Luminosity Detector
- Beam-Beam Deflection and Background Concerns for CEPC Fast Luminosity Detector
- Conclusion and Next to do

Description for CEPC Fast Luminosity Monitor System

- Crab-waist scheme for CEPC to achieve high luminosity
  - Beam size very small (horizontal: 14 μm; vertical: 36 nm)
  - Luminosity sensitive to the stability of beam jitter(like ground motion)
- Orbit feedback system at IP to maintain an optimum collision and maximize the luminosity
- Two possible methods for IP orbit feedback system

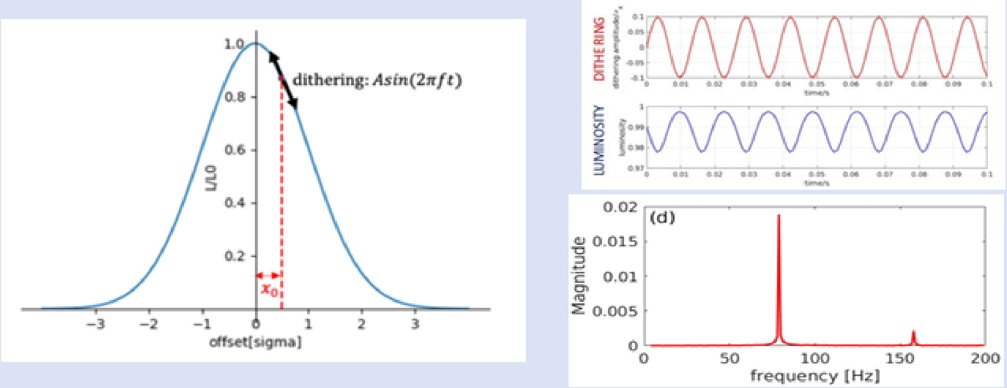
Vertical IP orbit feedback——**Beam-beam deflection driven method**



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

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

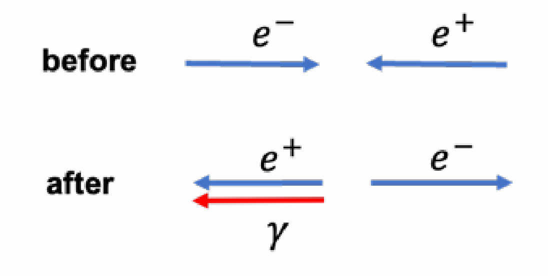
Horizontal IP orbit feedback——**Luminosity driven method**



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

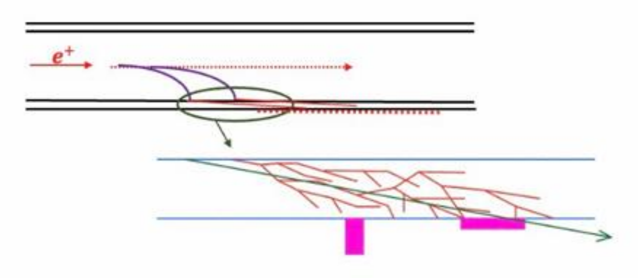
Description for CEPC Fast Luminosity Monitor System

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

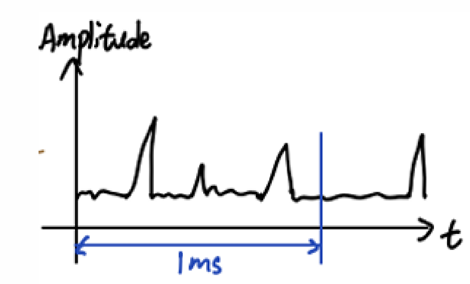


Luminosity	Cross section	Number of Bhabha	Aimed precision	Required fraction
5×10^{34}	0.127 barn	6.35×10^{6} in 1ms	2% in 1ms	4×10^{-4}

- The low energy Bhabha electrons hit the beam pipe downstream of IP



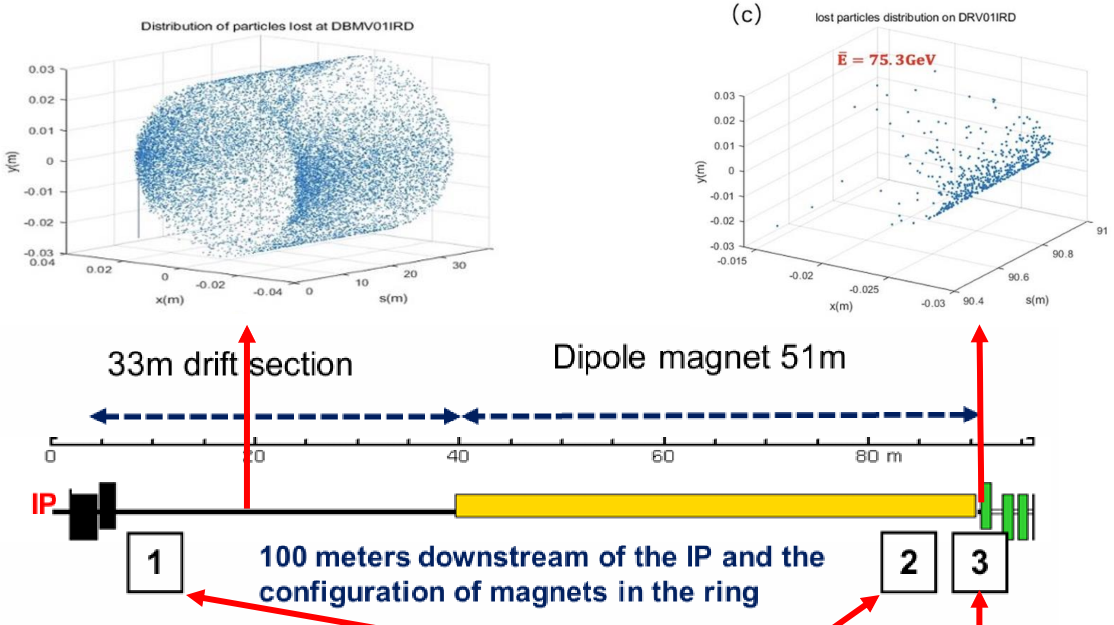
- The detectors put outside the beam pipe to capture secondary particles and provide the luminosity information



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

Description for CEPC Fast Luminosity Monitor System

- Downstream of IP 100 m :
  - 3 quadrupoles (strong defocusing in the horizontal direction)
  - 33 m drift section (some low-energy electrons are likely to be lost)
  - 51 m dipole magnet (deflects electrons towards inner side)
  - Additional drift sections, magnets and other elements….
- Detector installed position:
  - Position 1 and Position 3
  - Position 2 inside the dipole magnet (spatial constraints)

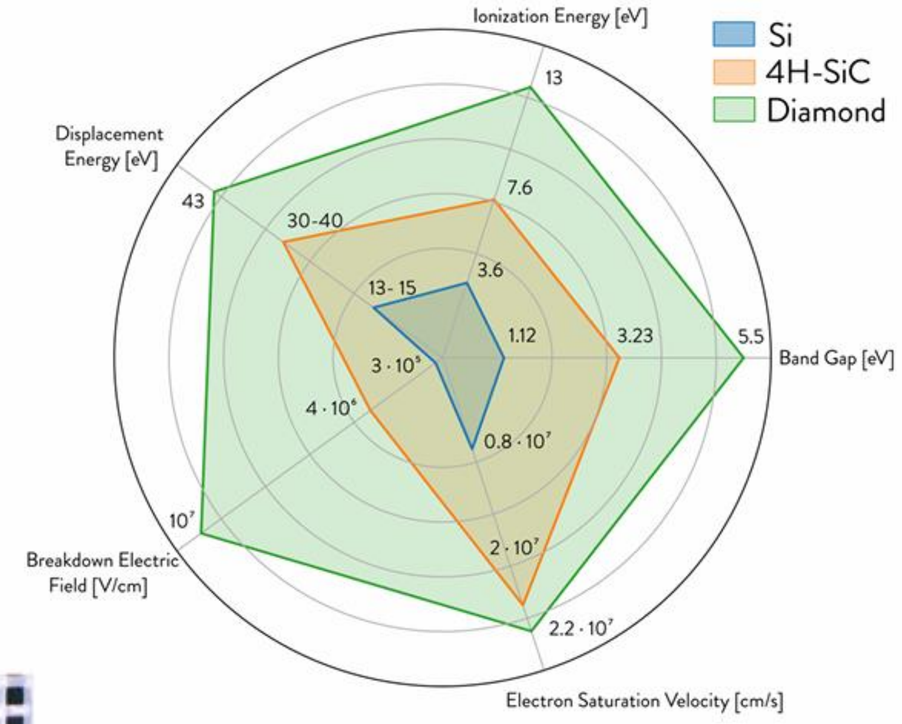


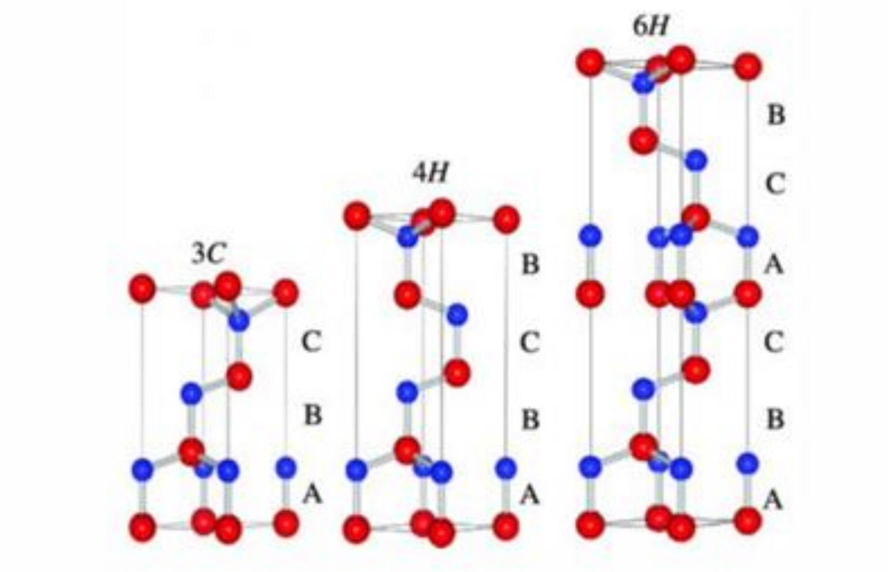
	Position1	Position2	Position3
Distance from IP	10m	84m	90.5m
Average Number detected/collision	3.4(two sides)	3(one side)	3.2(one side)
Average Number detected/ms	2830	2500	2670
Expected Measured Precision	1.9% @1kHz	2.0% @1kHz	1.9% @1kHz
Average Energy of scattered electron	24GeV	70GeV	75.3GeV
Average Hitting Angle	1.7×10^{-4}rad	7×10^{-4}rad	7×10^{-4}rad
Maximum Secondary Particle Position	88mm	104mm	105mm
Detection Area	$5 \times 20cm^2$	$3 \times 15cm^2$	$3 \times 15cm^2$
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		

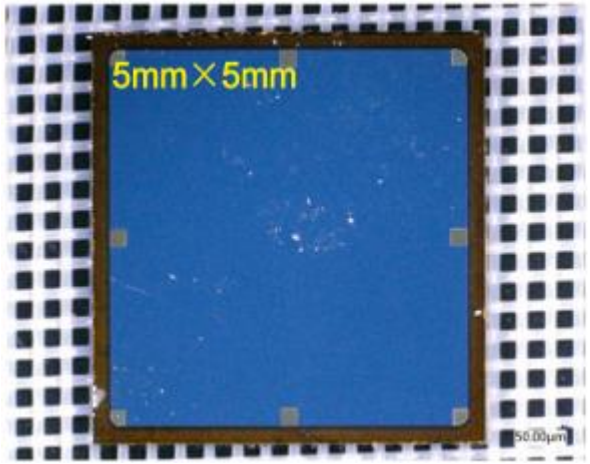
[1]M.Li, P.Bambade, D.Wang, H.Shi, S.Bai, J.He et al. Preliminary design consideration for CEPC fast luminosity feedback system, Radiation Detection Technology and Methods 9 (2025) 41.

Introduction for 4H-SiC detector

- Wide bandgap semiconductor (3.26 eV)
  - low leakage current
  - insensitivity to visible light
  - high breakdown field and saturation velocity
  - potentially higher radiation hardness, no cooling needed
  - high ionization energy
  - limitations in epitaxial layer thickness and resistivity
- Material not new but now available in higher quality (MOS technologies)

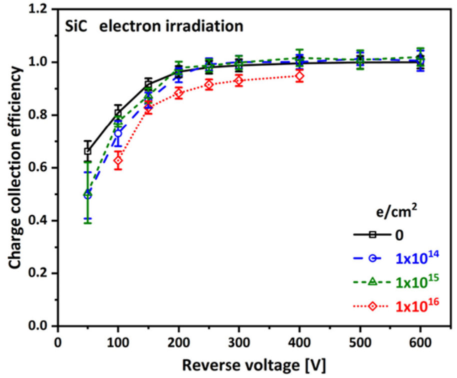


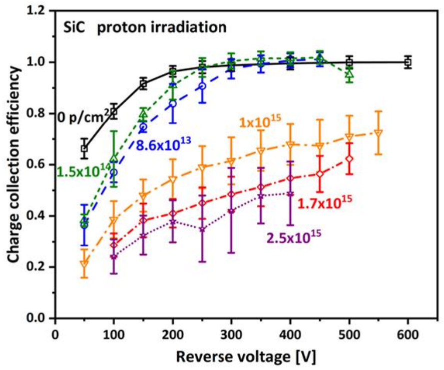


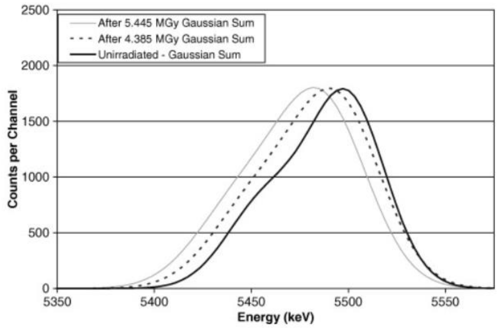


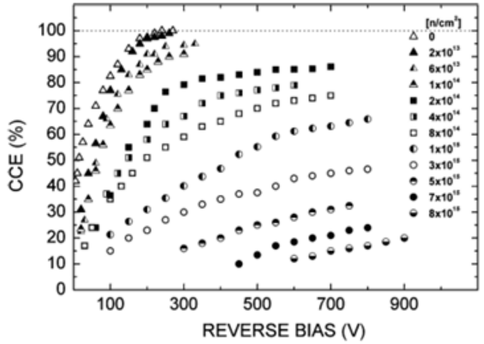
Introduction for 4H-SiC detector

- Under 5.445 MGy gamma irradiation:
  - The full width at half maximum (FWHM) of the peak increased by 17%
  - The energy shifted by 0.24% relative to the unirradiated detector for the 238Pu alpha source.
  - Both of these changes are negligible
- Electron irradiation at 2 MeV：
  - 1×10^{16} e/cm^2: CCE decreases to 90%
- Neutron irradiation at 1 MeV:
  - 1×10^{15} n/cm^2: the diodes maintain the charge collection efficiency (CCE) of 80%
  - 8×10^{15} n/cm^2: CCE decreases to 20%
- Proton irradiation at 24 GeV:
  - 2.5×10^{15} p/cm^2: CCE decreases to 45%
- X-ray irradiation indicate that an irradiation dose of 1 MGy does not affect the performance of the 4H-SiC detector.[Poster D01]







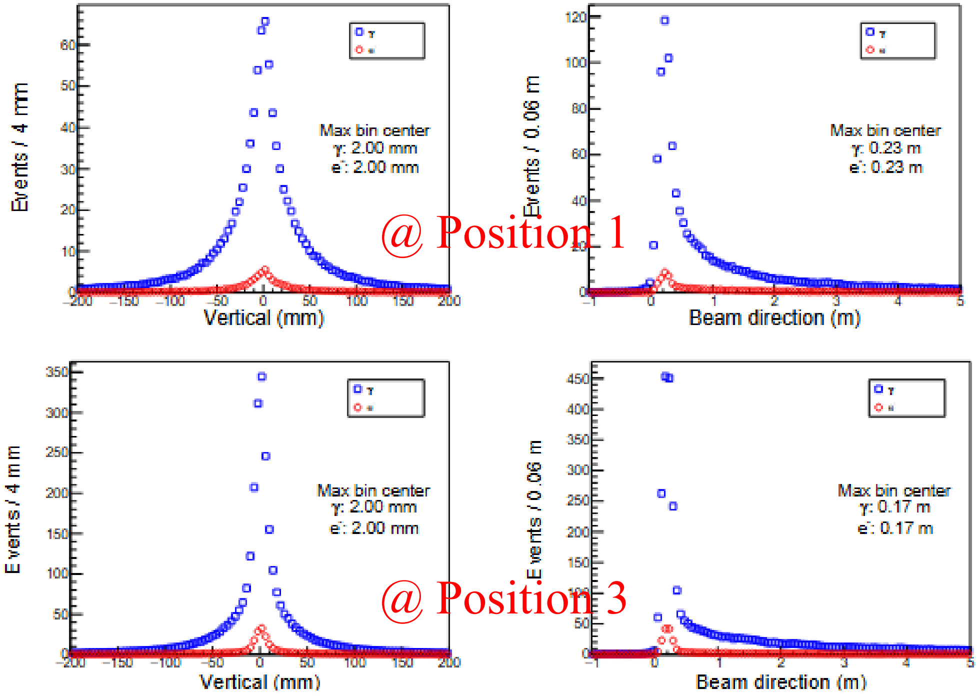


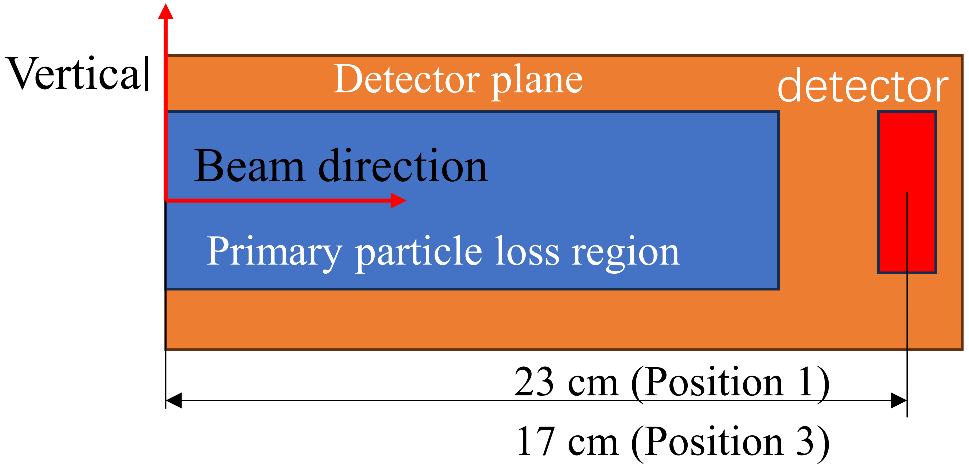
[1]F.H. Ruddy and J.G. Seidel, The effects of intense gamma-irradiation on the alpha-particle response of silicon carbide semiconductor radiation detectors, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 263 (2007) 163.
[2]F. Nava, A. Castaldini, A. Cavallini, P. Errani and V. Cindro, Radiation Detection properties of 4H-SiC Schottky Diodes Irradiated up to 10^{16}n/cm^2 by 1 MeV Neutrons, IEEE Transactions on369Nuclear Science 53 (2006) 2977.370
[3]J.M. Rafí, G. Pellegrini, P. Godignon, S.O. Ugobono, G. Rius, I. Tsunoda et al., Electron, Neutron,371and Proton Irradiation Effects on SiC Radiation Detectors, IEEE Transactions on Nuclear Science 67372(2020) 2481.373

Simulation Discussion for CEPC Fast Luminosity Detector

- Secondary particle:
  - Generated by the interaction between primary electrons and beam pipe
  - Captured by the detector and generates a signal
  - Photons dominant (87%), with 7% electrons
- Secondary particle distribution:
  - Detector plane: tangent to the outer wall of the beam pipe, ±31 mm in horizontal, detector mounting plane
  - Statistical distribution of secondary particles in the detector plane
  - Vertical distribution: symmetrical distribution with respect to the origin
  - Beam direction: 23 cm (Position 1) and 17 cm (Position 3) from one end of the primary electron loss region

	N_{sp}/N_{total}(%) at Position 1		N_{sp}/N_{total}(%) at Position 3
Secondary particle species	-31 mm detector plane	31 mm detector plane	-31 mm detector plane
γ	87.86	87.67	86.93
e^-	7.19	7.32	7.80
others	4.95	5.01	5.27S
total	100	100	100

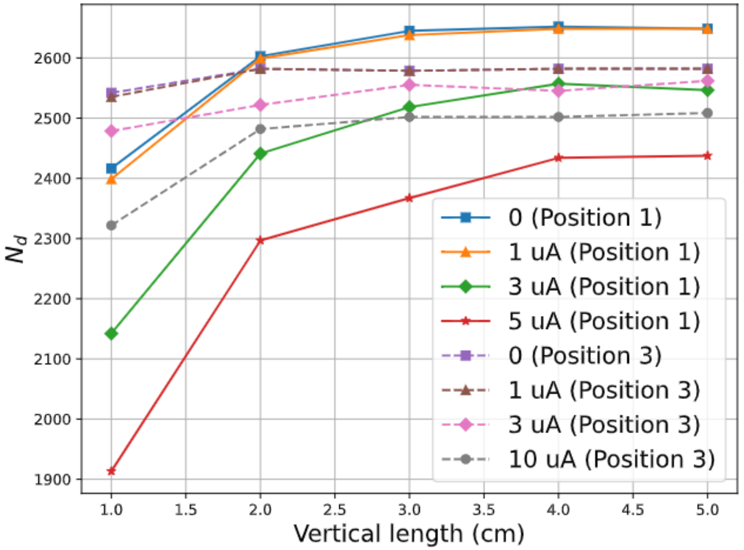


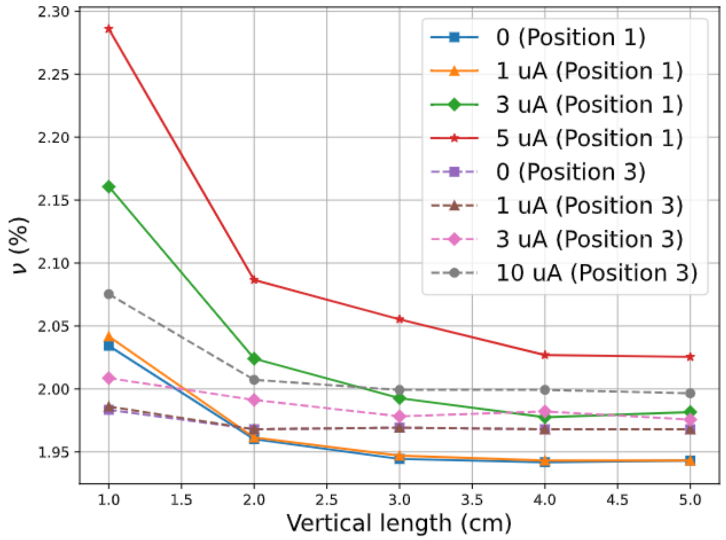


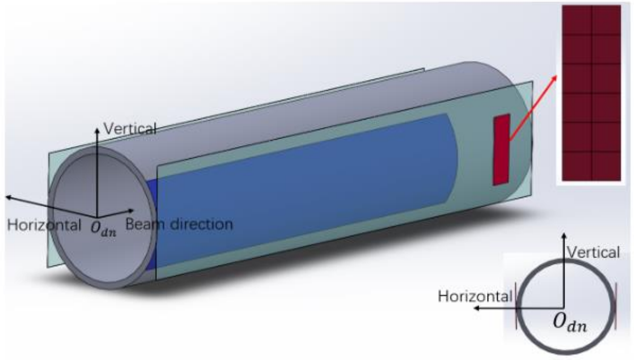
Simulation Discussion for CEPC Fast Luminosity Detector

- Fast luminosity detector 2% precision requirement:
  - 804 bunch crossing within 1 ms, bunch space: 600 ns (Low power Higgs mode)
  - Average 3.4 and 3.2 particles interact with the beam pipe at position 1 and position 3 per bunch crossing, respectively. (Poisson distribution)
  - Precision $\nu \leq 2\%$, the number of detected Bhabha electrons $N_d \geq 2500$ (within 1 ms)
- Detector dimension optimization:
  - The entire detector is constructed by 5mm × 5mm pixels
  - The detector length in the beam-direction is fixed at 1 cm, while the vertical length varies
  - Different equivalent input current noise levels (0, 1uA, 3uA, 5uA, 10uA) are considered

$$\nu = \frac{1}{\sqrt{N_d}} < 2\%$$



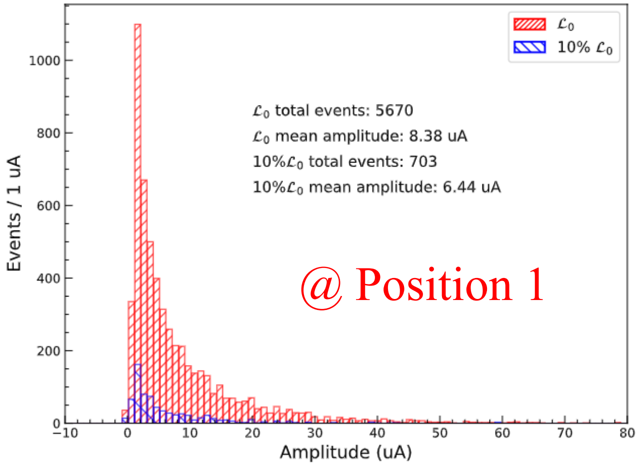


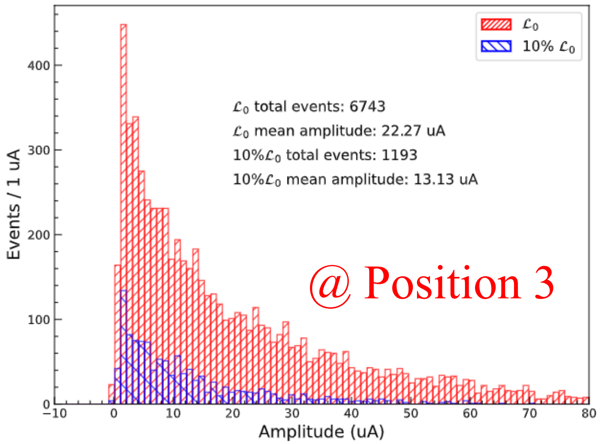


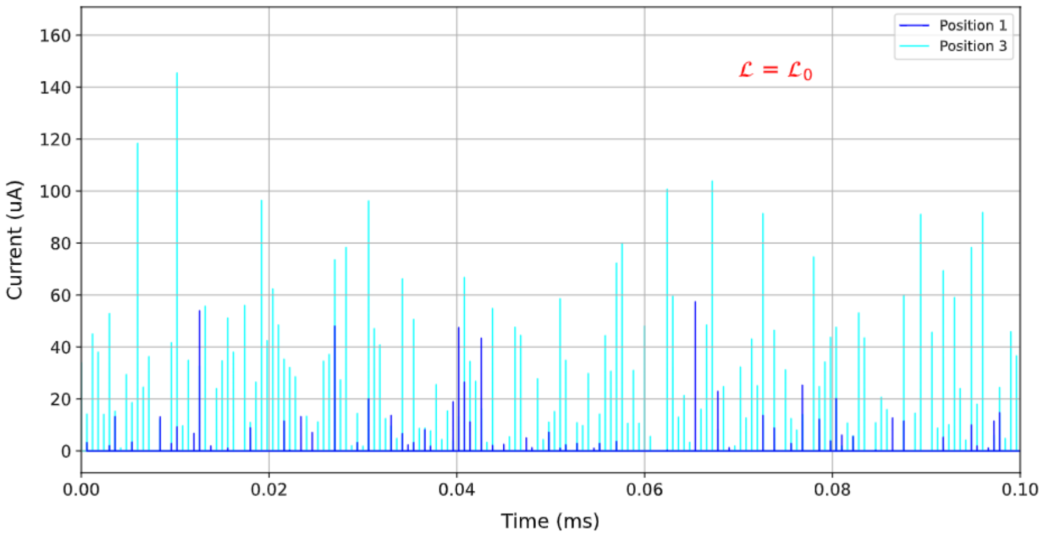
- The final determined detector dimension is 1 cm (beam direction) × 3 cm (vertical length), 12 pixels in total.
- The noise threshold at position 1 is 3 μA, while the noise threshold at position 3 is 10 μA.

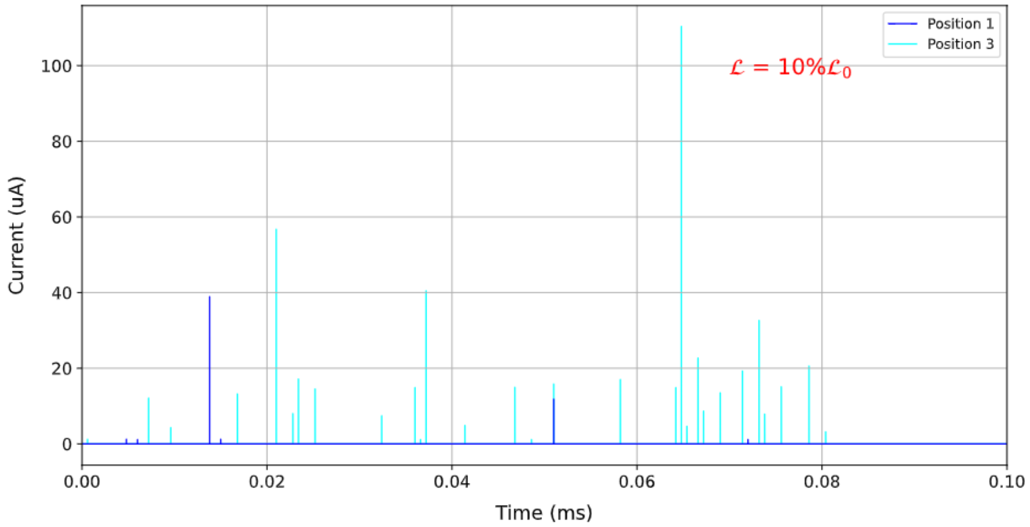
Simulation Discussion for CEPC Fast Luminosity Detector

- Luminosity fluctuation ➡ detector' response change
  - For a single pixel, different signal responses at nominal luminosity and 10% of nominal luminosity
  - For the entire detector, significant differences in the number and amplitude of the signals.









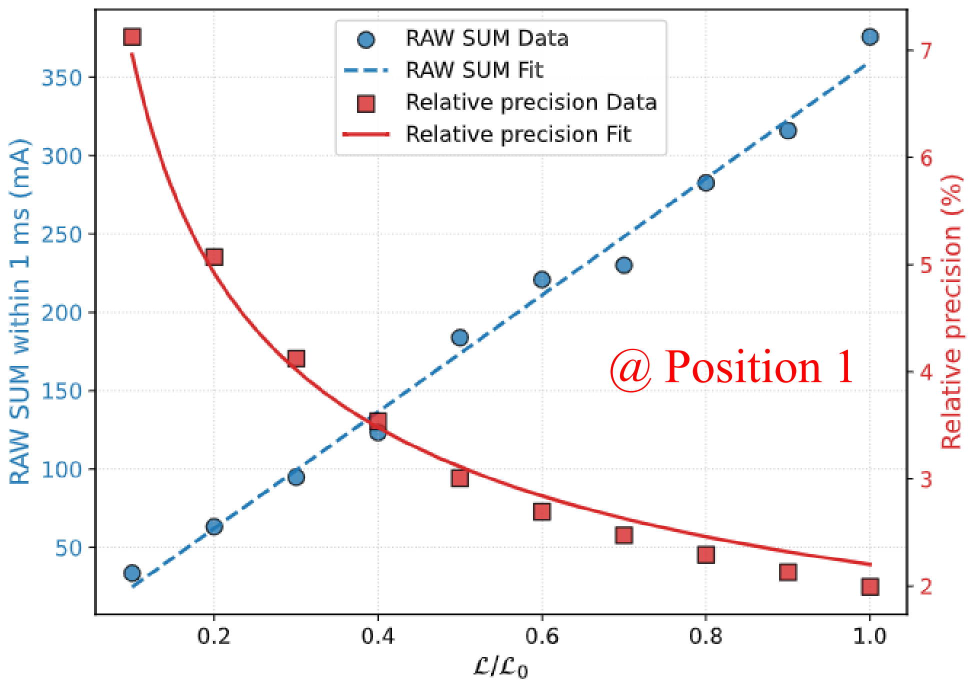
Simulation Discussion for CEPC Fast Luminosity Detector

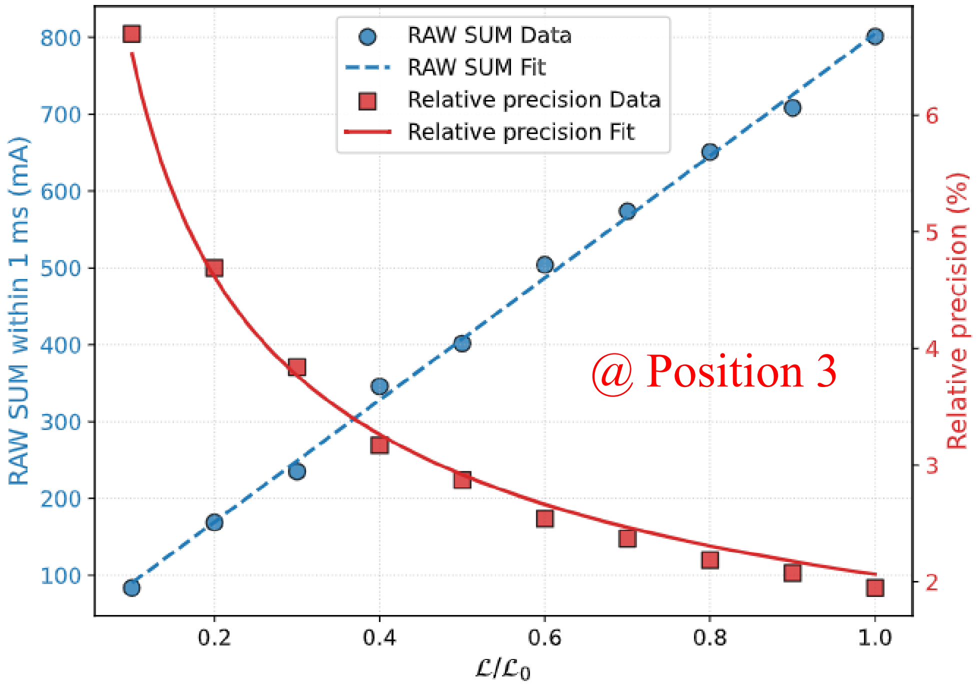
- The relationship between detector RAW SUM and luminosity
  - Assuming the sampling frequency of the DAQ is 10 GHz
  - Define RAW SUM:
    - s signifies the sampling points within 1 ms
    - p denotes the channel associated with each pixel within the single-sided detector
    - j represents the signals generated by the detectors situated on both sides of the beam pipe at Position 1

$$\text{RAW SUM} = \sum_{j=1}^{2} \sum_{s \in \mathcal{S}} \sum_{p \in \mathcal{P}} i_j(s,p) \quad \text{at Position 1}$$

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

- The relative precision under different luminosity conforms to $\nu \propto \frac{1}{\sqrt{L}}$





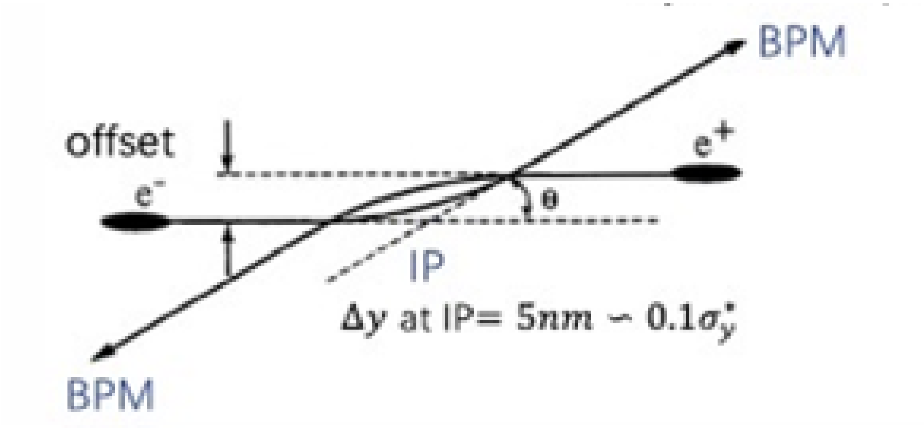
Beam-Beam Deflection and Background Concerns for CEPC Fast Luminosity Detector

- Beam-Beam Deflection:
  - originates from the electromagnetic interaction between the electron and positron bunches
  - the principle of BPM measurement of the orbit offset
- Beam-Beam Deflection mainly impacts position 1, with almost no effect on position 3
- 10% reduction of detected Bhabha electrons after considering beam-beam deflection(the worst case)
- After considering beam-beam deflection, the detector precision ν_b becomes 1.04ν

$$\left(\frac{N_w}{N_{wo}}\right)_{max} = 90\%$$

$$\nu_b = \frac{1}{\sqrt{N_b}},$$

$$N_b = \frac{N_w}{N_{wo}} \times N_d$$



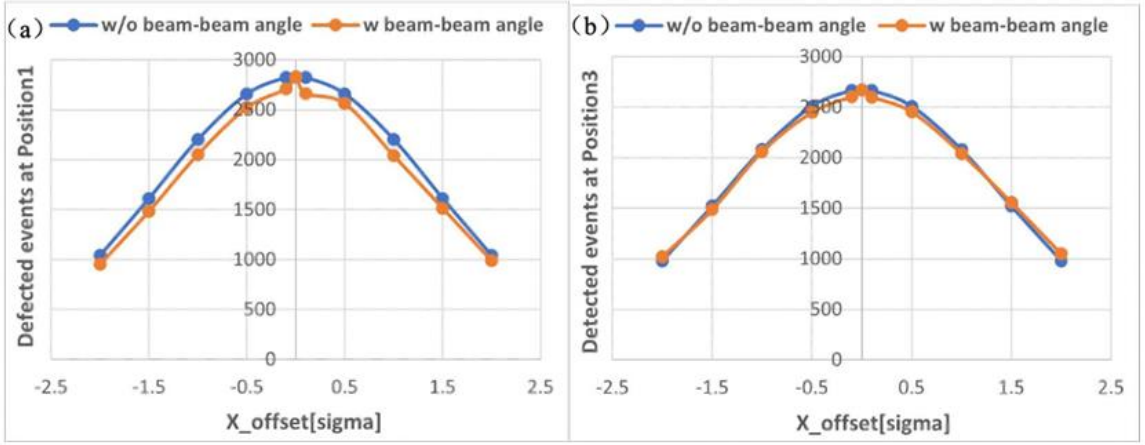


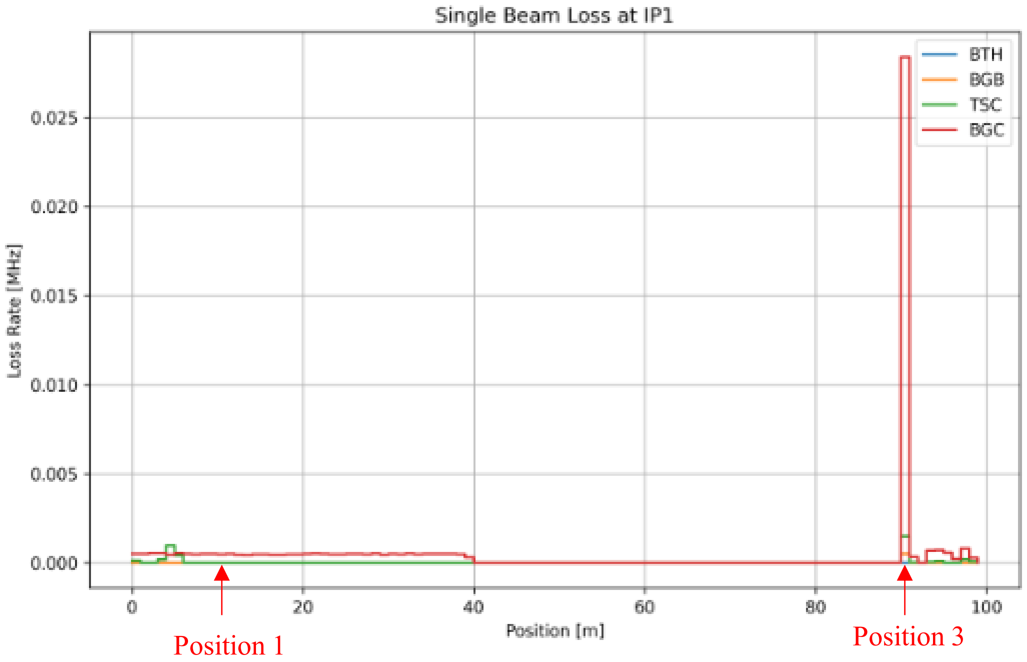
Fig. 12 Expected detected Bhabha events varies with IP offset at Positions 1 and 3

[1]M.Li, P.Bambade, D.Wang, H.Shi, S.Bai, J.He et al. Preliminary design consideration for CEPC fast luminosity feedback system, Radiation Detection Technology and Methods 9 (2025) 41.

Beam-Beam Deflection and Background Concerns for CEPC Fast Luminosity Detector

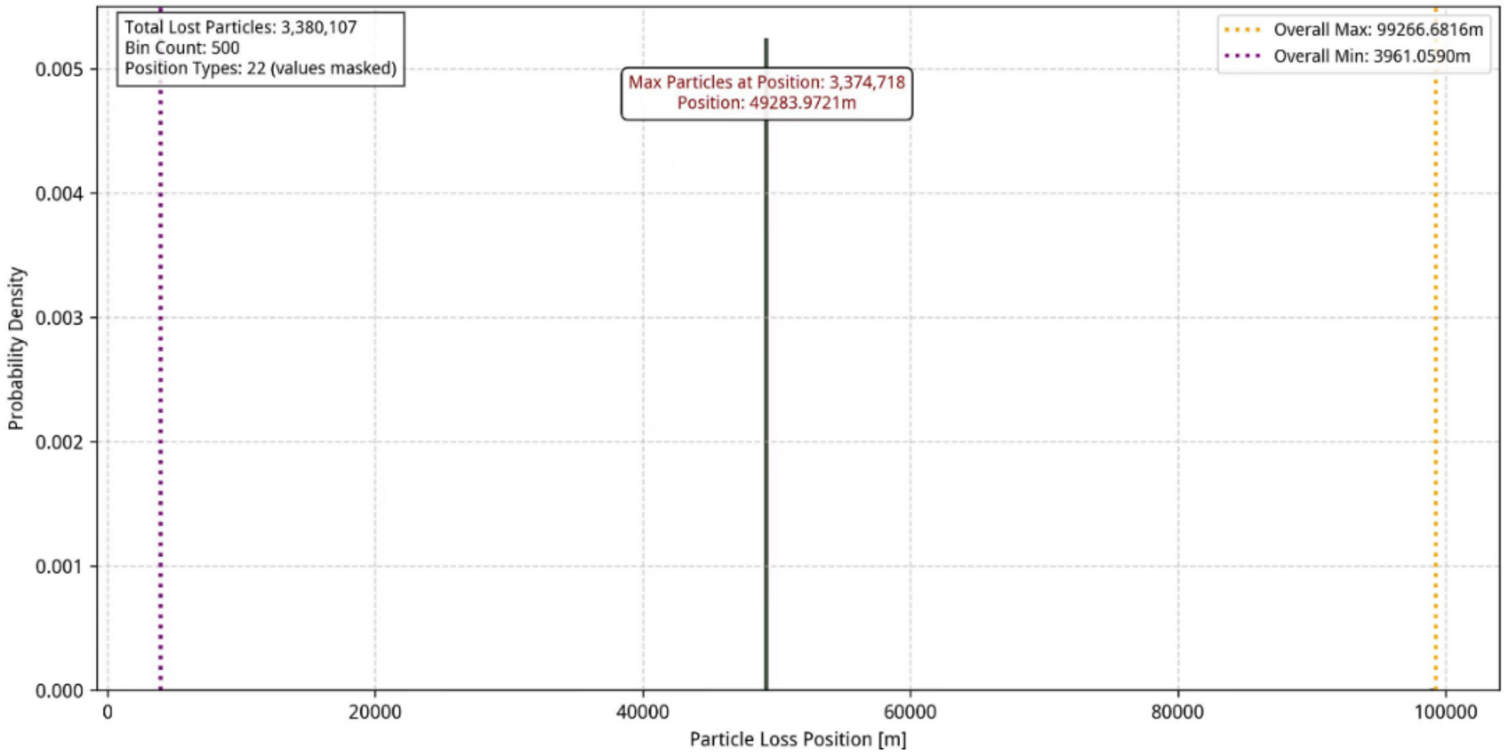
- Single-Beam background:
  - 4 single-beam background are concerned: beam-thermal photon scattering (BTH), beam-gas scattering (Coulomb scattering (BGC) and Bremsstrahlung scattering (BGB)), and Touschek scattering (TSC)
  - BGC dominants, and the single-beam background has losses at position 1 and position 3

	Single-Beam background	Primary electrons by radiative Bhabha
Position 1	7×10^{-5} per bunch crossing	3.4 per bunch crossing
Position 3	2×10^{-2} per bunch crossing	3.2 per bunch crossing



Beam-Beam Deflection and Background Concerns for CEPC Fast Luminosity Detector

- Injection background:
  - Top-up injection
  - Aperture blocks to minimize the impact of injection background on the collision region
  - With beam-beam impact concerned
  - 50 million particles are injected and run around the ring for 200 turns
- Particle loss is mainly concentrated at 49.28 km downstream of the IP, with no loss at position 1 and Position 3(10 m and 90.5 m downstream of the IP)



Conclusion and Next to do

- Conclusion:
  - The dimension (1 cm × 3 cm) and position (Position 1 offset 23 cm, Position 3 offset 17 cm) of the detector installation have been determined.
  - Detector RAW SUM within 1 ms has a good linear relationship with luminosity, and therefore can be used for real-time luminosity monitoring.
  - The impact of Beam-Beam deflection, Single-beam background and Injection background has been concerned
- Next to do:
  - 4H-SiC device fabrication and test
  - Design for multi-channel ultrafast readout electronics of the detector
  - A fast luminosity monitor system prototype and Design validation at BEPCII

Thanks