中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

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CEPC

Preliminary Design Considerations for IP Luminosity Feedback System at CEPC

Meng Li

P. Bambade, D. Wang, H.Y. Shi, S. Bai, J. Gao

Mini-workshop on CEPC fast luminosity feedback
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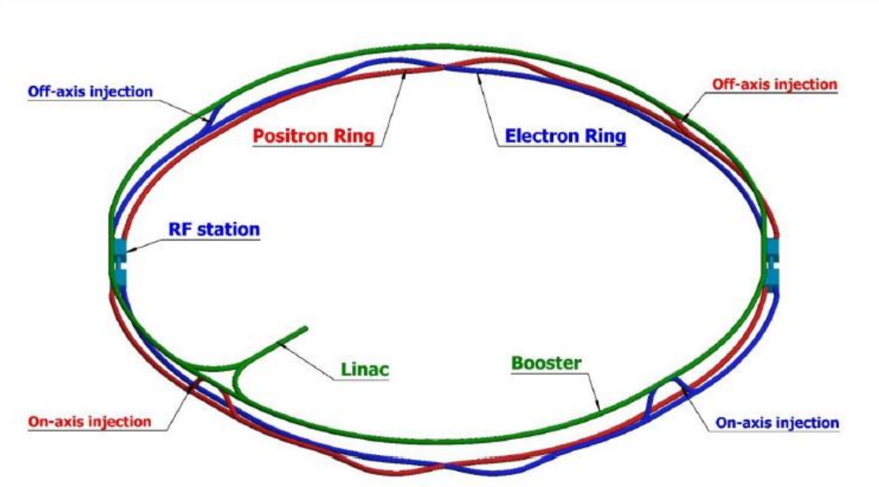
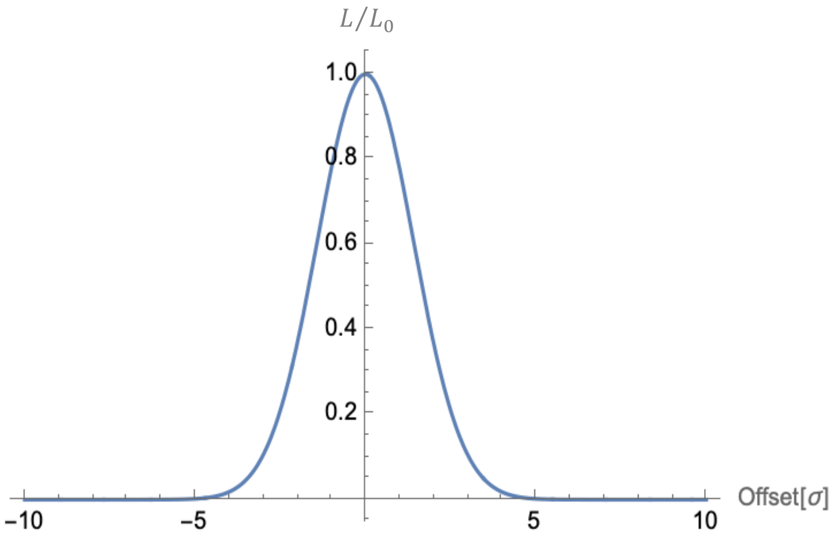
Motivation

- **CEPC**: **100-km double-ring e^+e^- collider**
  - ✓ Four energy modes: Z (45.5 GeV), W (80 GeV), **Higgs (120 GeV)**, $\bar{t}t$ (180 GeV)
  - ✓ Main scientific goal: operate as a **Higgs factory**
  - ✓ Design luminosity in Higgs mode: 5×10^{34} cm^{-2} s^{-1}



- **To achieve high luminosity**, CEPC adopts the **nano-beam collision scheme**
  - ✓ Strong focusing at IP → $\beta_y^* = 1\text{mm}$, $\varepsilon_y^* = 0.64\text{nm}$→ $\sigma_y^* = 36\text{nm}$
    - → **extremely small beam size**
    - →**Luminosity becomes extremely sensitive to transverse orbit offset**
      - - $0.1\ \sigma_y^*$ offset (3.6 nm)→ ~1 % luminosity loss
      - - Ground motion (HEPS data) already reaches this level at ~5 Hz

Therefore, **a fast IP orbit feedback system** (ms response) **is essential to maintain optimal collision** and maximize integrated luminosity.



- **In addition**, **a fast and precise luminosity monitor is required for**:

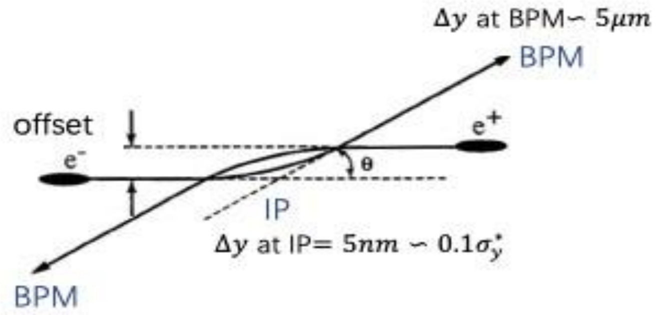
Machine tuning (commissioning, ramp-up) and long-term luminosity optimization

Two Candidate Feedback Methods

☐ Considered two possible methods for the IP orbit feedback system at CEPC (like SuperKEKB)

- **Beam-beam deflection driven method**

Based on the measurement of the beam orbit around the IP. The offset at the IP is too small to be accurately measured, but this small offset can be converted into a large offset due to the mutual electromagnetic deflection as the beams propagate forward and collide. **By measuring this offset with BPMs upstream and downstream of the IP**, we can obtain the offset at the IP and the sign. If accuracy of BPM is precise enough, we may maintain the optimum collision with almost no luminosity loss. We usually prioritize this method for this reason.

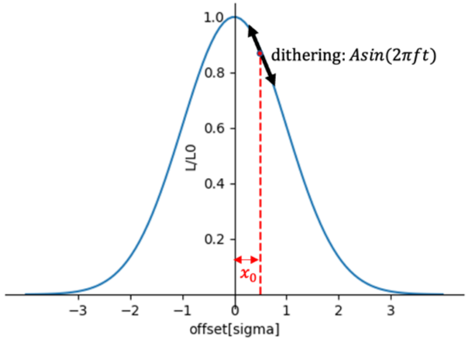


$$\Delta y'_{\pm} = -\frac{r_e N_{\mp}}{\gamma_{\pm}\sigma^*_{y\mp}\left(\tilde{\sigma}^*_{x\mp} + \sigma^*_{y\mp}\right)}\Delta y_{IP}$$

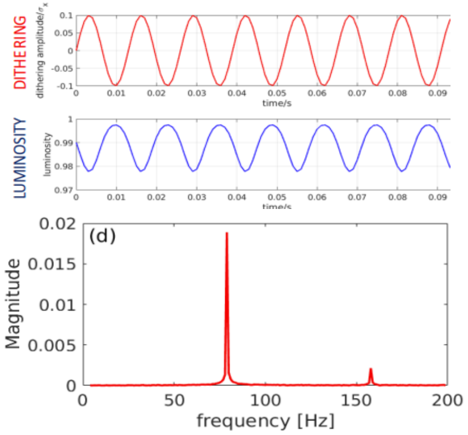
$$\Delta \mathbf{y}_{\mathbf{BPM}} = \sqrt{\boldsymbol{\beta}^* \boldsymbol{\beta}_{\mathbf{BPM}}}\Delta \mathbf{y}'$$

- **Luminosity-driven system**

Based on measurements of the luminosity. Due to the luminosity being a symmetrical function of offset, we can only obtain the offset between two beams but cannot easily know its sign. And some other effects (beam size and intensity) may also cause luminosity changes at relatively low frequency. To solve this problem, we should introduce a dithering with certain frequency, and then luminosity will change with same frequency, we can extract orbit shifts and correct them.



$$L(x) = L_0 exp\left(-\frac{[x_0 + Asin(2\pi f t)]^2}{2\Sigma_x^2}\right)$$



Evaluation of Beam-Beam Deflection for CEPC

- **Assume offset = $0.1\ \sigma^*_{x,y}$ caused by ground motion (~1 % luminosity loss)**
- **Use CEPC TDR parameters, BPM distance ≈0.9 m from IP**, beam-beam angular deflection can be estimated

CEPC [Unit]	β_x^*/β_y^* [m/mm]	σ_x^*/σ_y^* [μm/nm]	ξ_x^*/ξ_y^*	$\Delta x_{IP}/\Delta y_{IP}$ [μm/nm]	$\Delta x'/\Delta y'$ [μrad]	$\Delta x_{BPM}/\Delta y_{BPM}$ [μm]	SNR (0.2 μm res.)
Z	0.13/0.9	6/35	0.004/0.127	0.6/3.5	-0.1/-3.1	-0.1/-2.8	0.5 / 14
W	0.21/1.0	13/42	0.012/0.113	1.3/4.2	-0.5/-3.0	-0.4/-2.7	2.0 / 13.5
Higgs	0.30/1.0	14/36	0.015/0.11	1.4/3.6	-0.4/-2.5	-0.4/-2.2	2 .0 / 11
tt	1.04/2.7	39/113	0.071/0.1	3.9/11.3	-1.7/-2.6	-1.4/-2.4	7.0 / 12

- **Vertical: feasible** (SNR > 10 for all modes)

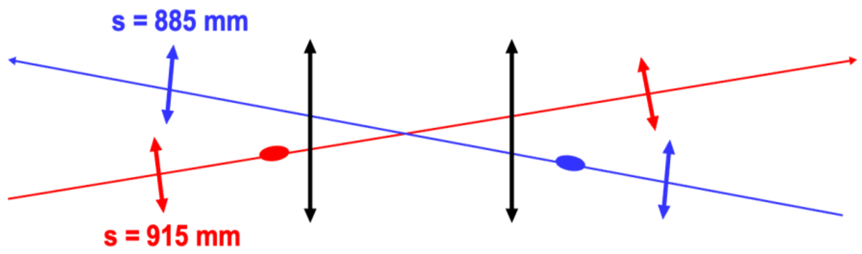
  Offset at BPM is sizable compared to typical expected BPM resolution

- **Horizontal: too weak** (Higgs: 0.4 μm, SNR ≈2) due to large crossing angle

  Difficult to measure such a small beam deflection.

- **Conclusion**: vertical → beam-beam deflection

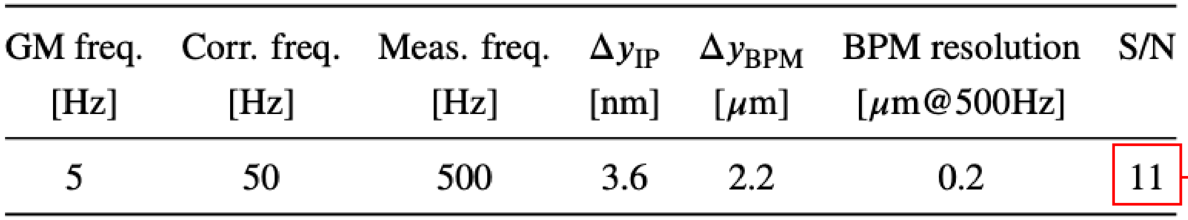
  horizontal → luminosity dithering



$$\Delta y'_{\pm} = -\frac{r_e N_{\mp}}{\gamma_{\pm}\sigma^*_{y\mp}\left(\tilde{\sigma}^*_{x\mp} + \sigma^*_{y\mp}\right)}\Delta y_{IP}$$

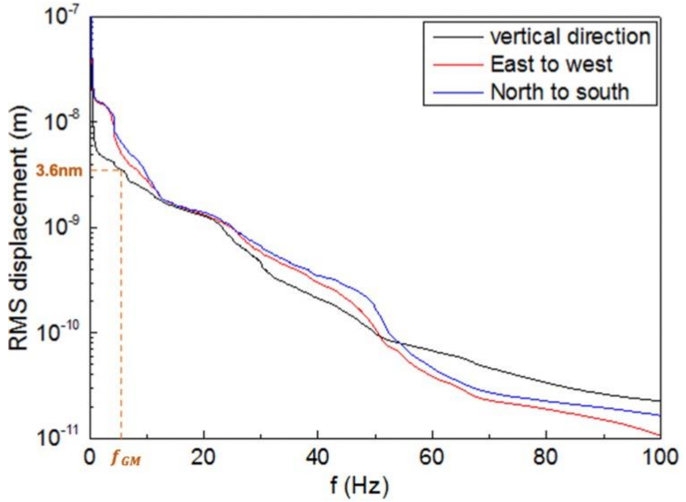
Vertical Feedback: beam-beam deflection method

- Baseline: Higgs mode 2.24 μm (smallest signal among the four energy modes)
- Allowable offset keep luminosity reduction within 1%: 0.1 σ_y^*= 3.6 nm
- Need to correct ground motion up to ≈5 Hz (used HEPS ground motion data)

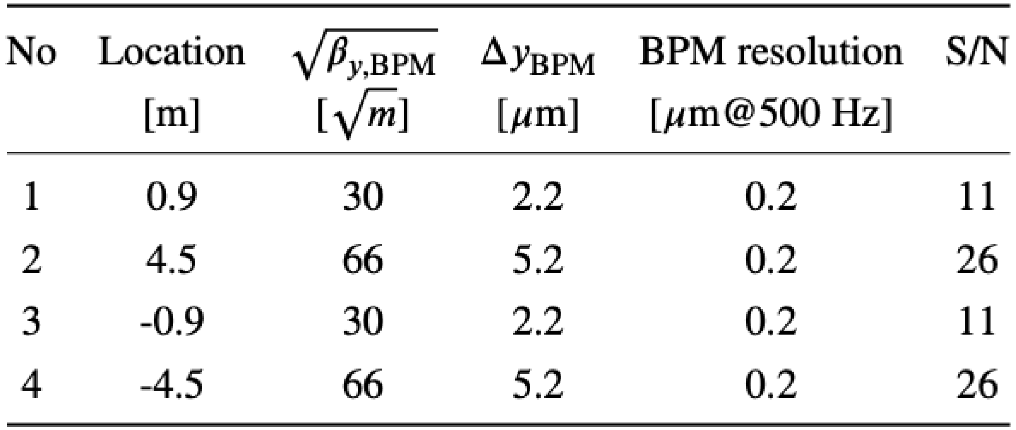


GM freq. [Hz]	Corr. freq. [Hz]	Meas. freq. [Hz]	Δy_{IP} [nm]	Δy_{BPM} [μm]	BPM resolution [μm@500Hz]	S/N
5	50	500	3.6	2.2	0.2	11

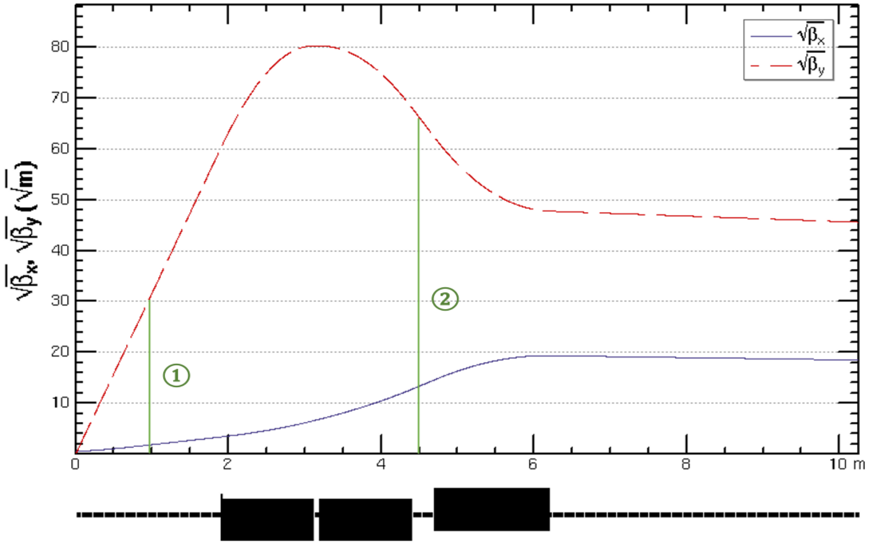
→ Good enough to accurately measure orbit changes



- **BPM layout**: two pairs symmetrically at 0.9 m and 4.5 m from IP



No	Location [m]	$\sqrt{\beta_{y,\mathrm{BPM}}}$ [$\sqrt{m}$]	Δy_{BPM} [μm]	BPM resolution [μm@500 Hz]	S/N
1	0.9	30	2.2	0.2	11
2	4.5	66	5.2	0.2	26
3	-0.9	30	2.2	0.2	11
4	-4.5	66	5.2	0.2	26

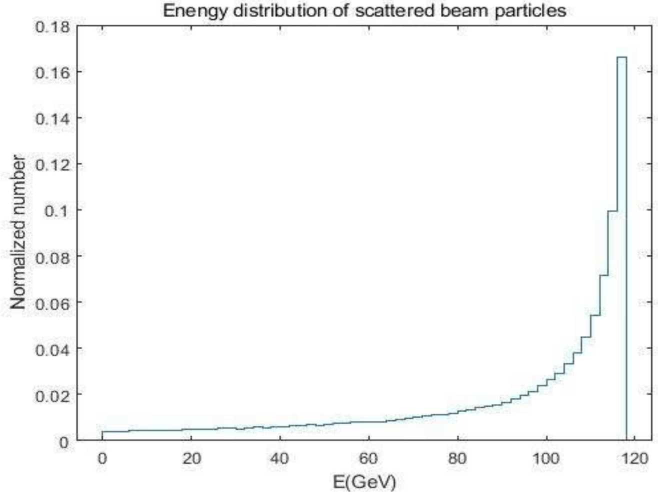


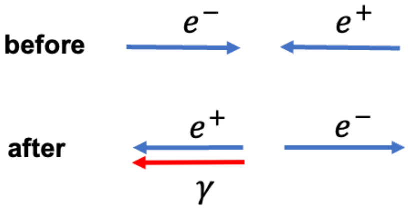
Advantages of multiple BPMs: cross-validation, improved precision, redundancy

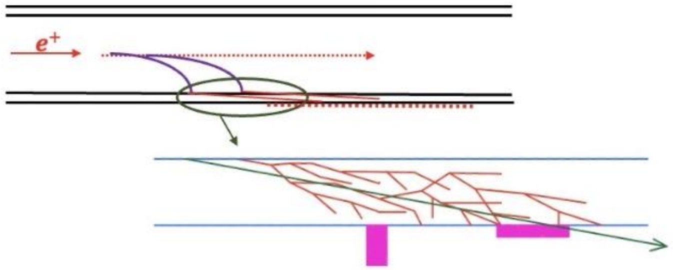
Horizontal Feedback: Luminosity Driven Method

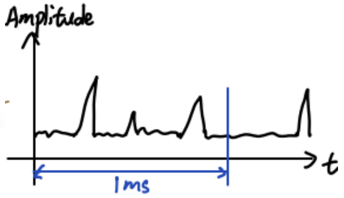
☐ Fast luminosity monitor

- ✓ Based on **radiative Bhabha scattering process at zero degree:** $e^+e^- \rightarrow e^+e^-\gamma$
- ✓ **Large cross section** ~ 127 mbarn (Higgs mode)
- ✓ Bhabha **event rates proportional to the luminosity**: $N = \sigma \times \mathcal{L} \times \tau \times \epsilon \qquad v = \frac{1}{\sqrt{N}}$
- ✓ Only relative luminosity → $L \propto \frac{dN}{dt}$ → count the number and amplitude of signals









☐ Design goal (based on SuperKEKB experience)

- **Precision**: 2 % in 1 ms (for 1 kHz feedback)

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}

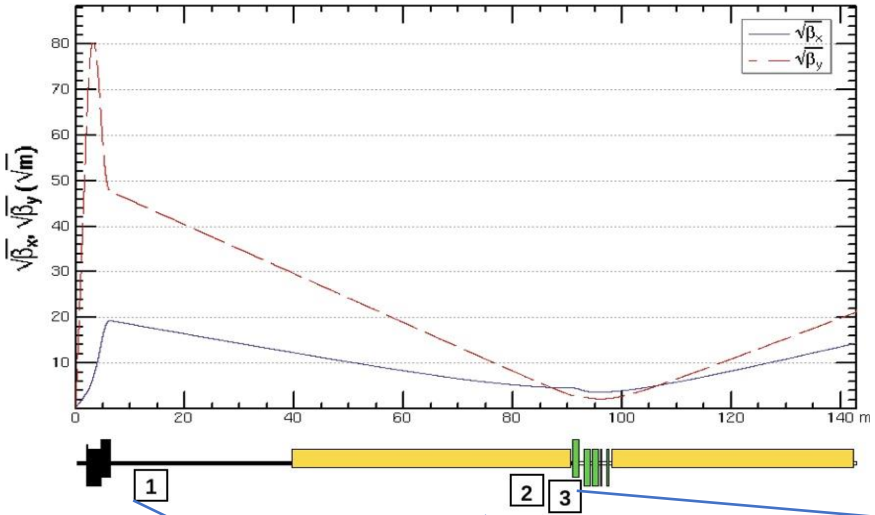
☐ Selection criteria for detector location

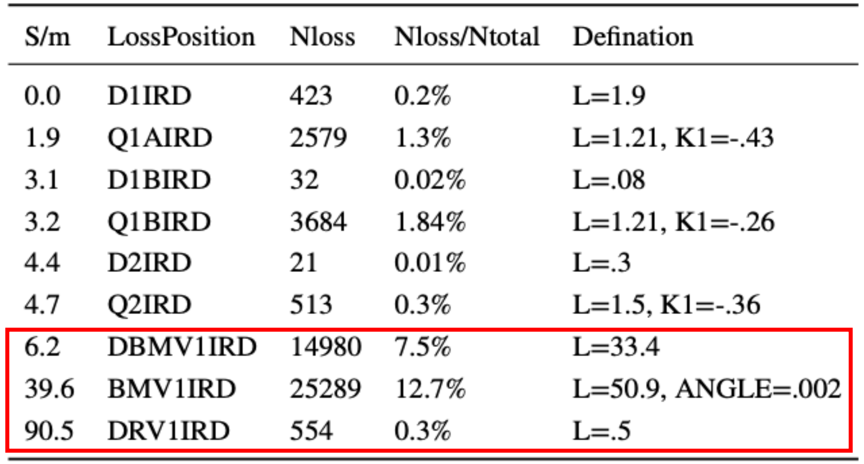
1. Loss fraction ≥ required value ($\geq 4\times10^{-4}$)
2. Radiative Bhabha dominates over other loss processes
3. Insensitive to beam-beam deflection (to ensure stable measurement)

Fast Luminosity Monitor: Simulation & Loss Distribution

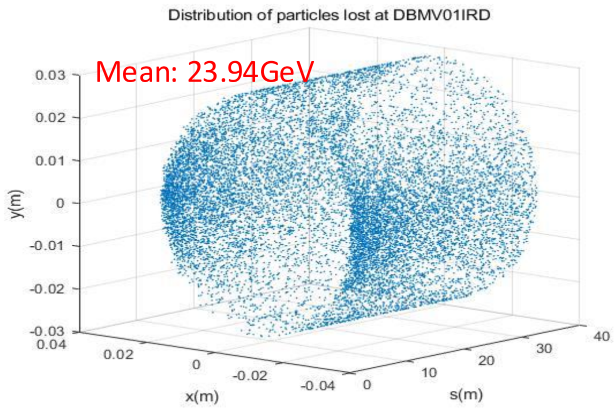
- **Simulation setup**:
- **BBBREM** (generate Bhabha events) + **SAD** (track to 100 m), 0-120 GeV
- Low-energy scattered electrons travel through:

three quadrupoles (Q1AIRD, Q1BIRD, Q2IRD) → 33 m drift (DBMV01IRD) →51 m bending magnet (BMV01IRD) → 0.5m drift after dipole (DRV1IRD)

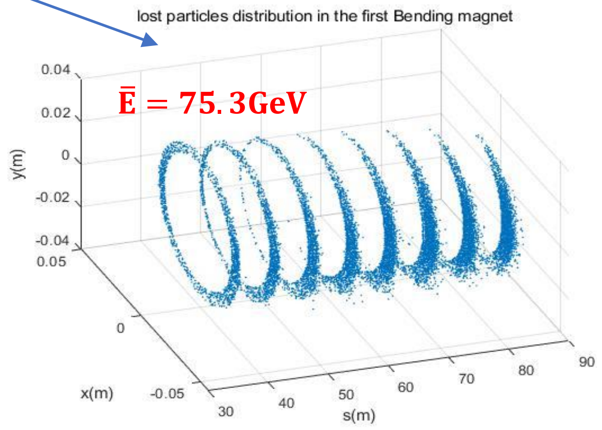




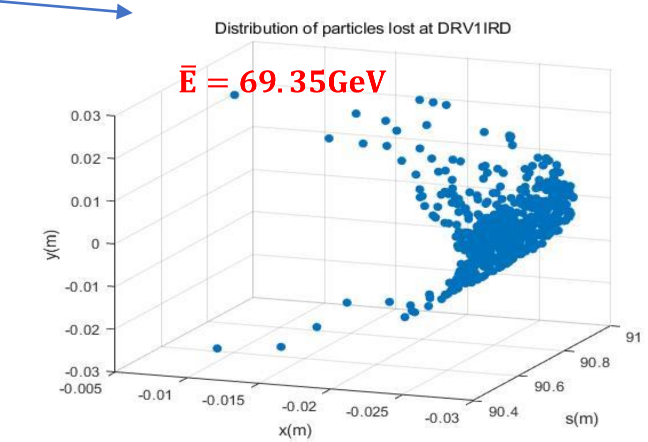
S/m	LossPosition	Nloss	Nloss/Ntotal	Defination
0.0	D1IRD	423	0.2%	L=1.9
1.9	Q1AIRD	2579	1.3%	L=1.21, K1=-.43
3.1	D1BIRD	32	0.02%	L=.08
3.2	Q1BIRD	3684	1.84%	L=1.21, K1=-.26
4.4	D2IRD	21	0.01%	L=.3
4.7	Q2IRD	513	0.3%	L=1.5, K1=-.36
6.2	DBMV1IRD	14980	7.5%	L=33.4
39.6	BMV1IRD	25289	12.7%	L=50.9, ANGLE=.002
90.5	DRV1IRD	554	0.3%	L=.5


Distribution of particles lost at DBMV01IRD

Mean: 23.94GeV

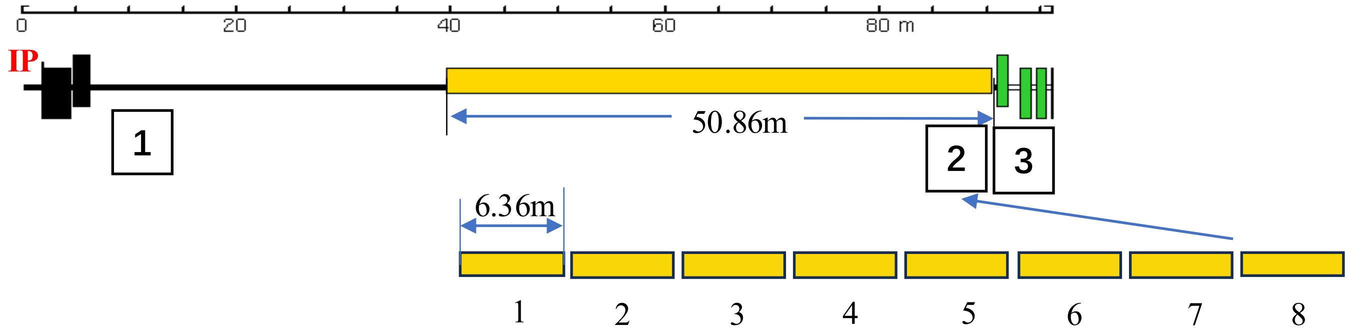

lost particles distribution in the first Bending magnet

$\bar{E} = 75.3\text{GeV}$


Distribution of particles lost at DRV1IRD

$\bar{E} = 69.35\text{GeV}$

Fast Luminosity Monitor: Candidate Positions & Optimal Choice



	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	88.32mm	103.85mm	104.91mm
Detector Size Assumed	$5 \times 20 cm^2$	$3 \times 15 cm^2$	$3 \times 15 cm^2$
Backgrounds	SR Photons in 1 Side	-	-
Beam-Beam Deflection Impact	sensitive	less sensitive	less sensitive
Detector Number	2	1	1
Detector Measurement Parameters	Peak value and number of signals within 1ms		
Detector Time Resolution	600ns		
Detector technology possibility	LGAD, SiC, Diamond		

Summary and outlook

- The implementation of a fast luminosity feedback system at the IP is crucial for CEPC to ensure optimal collision and achieve maximum luminosity.
- The proposed approach involves utilizing the beam-beam deflection driven method based on BPMs for vertical orbit feedback and a luminosity-driven method for horizontal feedback.
- Candidate positions for BPMs and luminosity detector have been identified.
- However, there is still more work to be done, such as the design of the BPM and feedback electronics, the design of detectors and data acquisition system, and the entire feedback system simulation from start to end, and so on.

Thanks for your attention

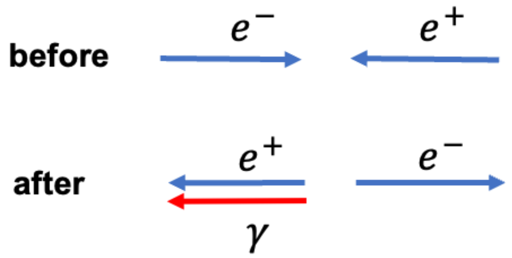
Horizontal IP orbit feedback

☐ Luminosity-driven method with a dithering system used for orbit feedback and luminosity optimization

- ➔ considering the weak beam-beam deflection and a lower required feedback speed (1kHz)

☐ The fast luminosity monitor based on radiative Bhabha at zero degree

--single Bremsstrahlung of of one beam particle in the field of an opposing beam particle



- ➔very large cross section (127mbarn)
- ➔ Bhabha particles produced at the IP is proportional to the luminosity

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

- ➔ 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}

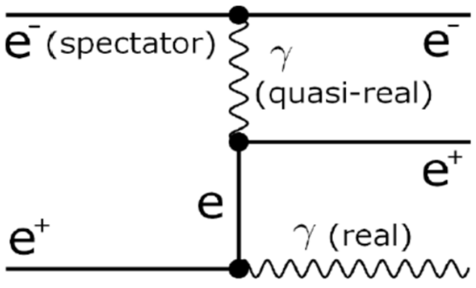
* need further review

Fast Luminosity Monitor working principle

- ☐ Radiative Bhabha scattering at zero degree — single Bremsstrahlung of single positron in the field of one electron.
- ☐ This process is also one of the main sources of particles losses in a very high luminosity e-e+ collider.
- ☐ Only relative luminosity →. $L \propto \frac{dN}{dt}$ → count the number of signals

$E\ (e^-) = 120GeV$

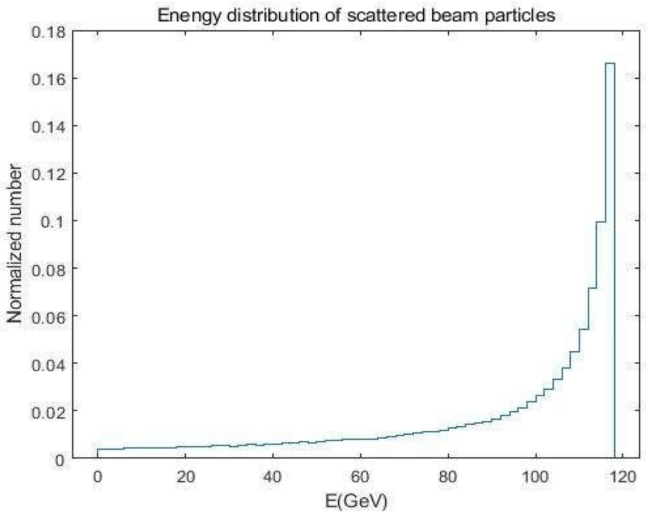
$E\ (e^+) = 120GeV$

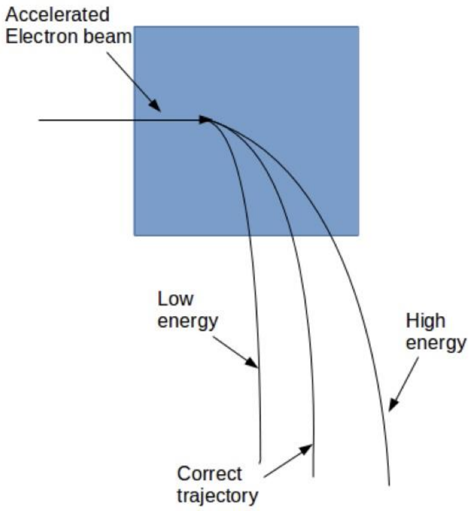


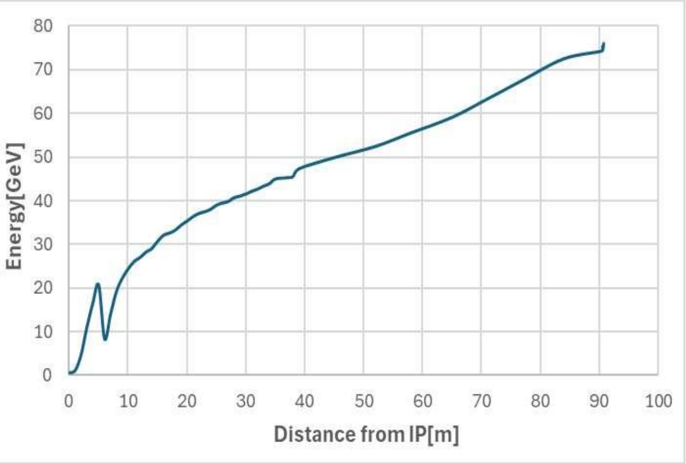
$E\ (e^-) = 120GeV$

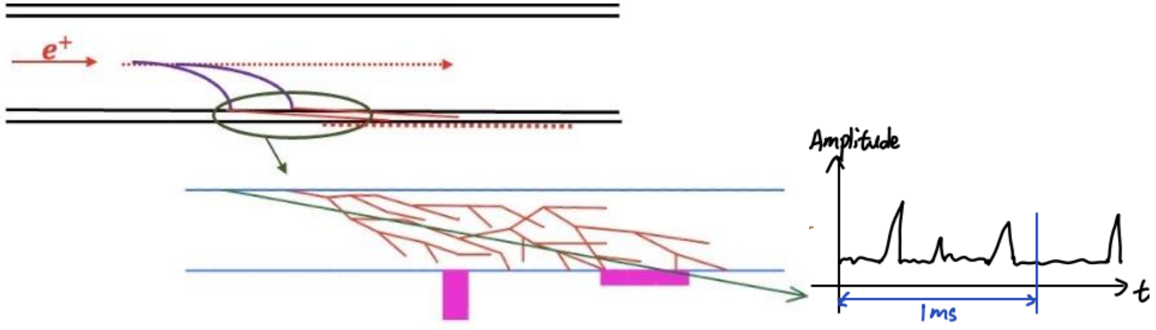
$E\ (e^+)$

$E\ (\gamma)$



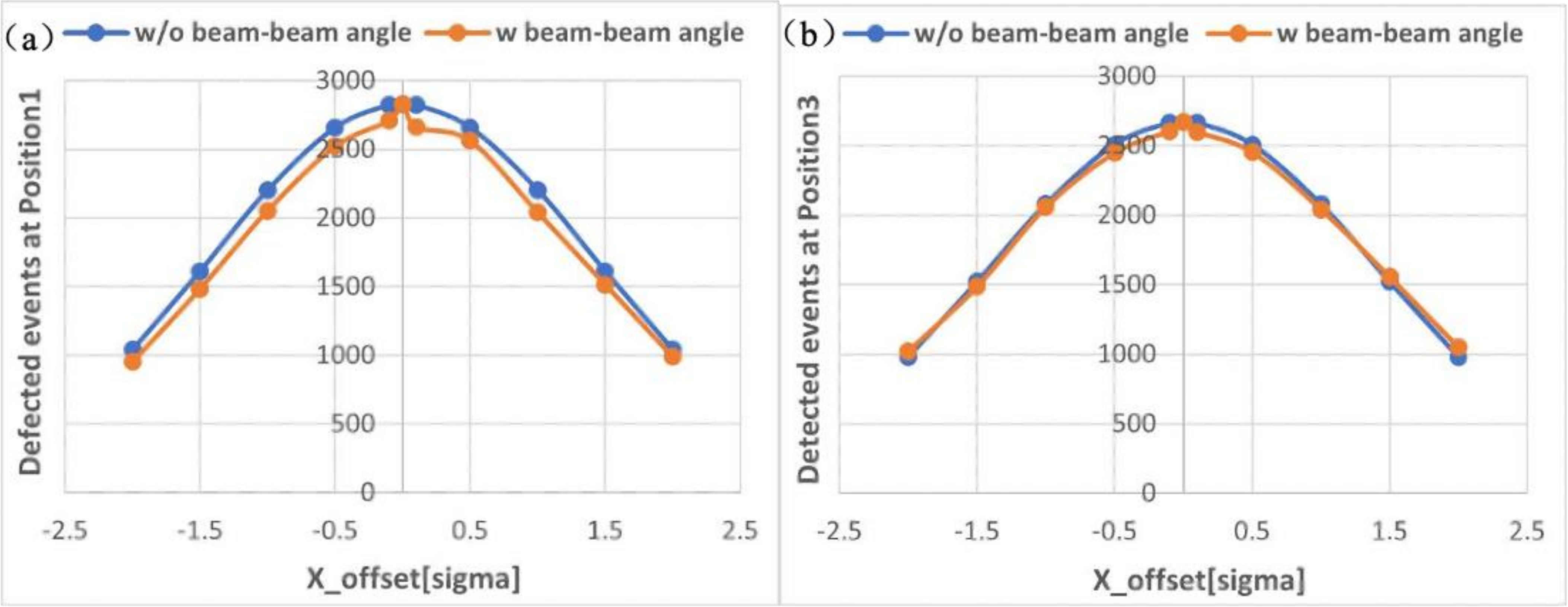






Position of fast luminosity monitor for CEPC

- Furthermore, the simulated expected number of Bhabha events that will be detected in different offset cases each millisecond for position 1 and position 3 shows an almost linear relationship with the offset at the IP and varies greatly, making it easy for detectors to measure.

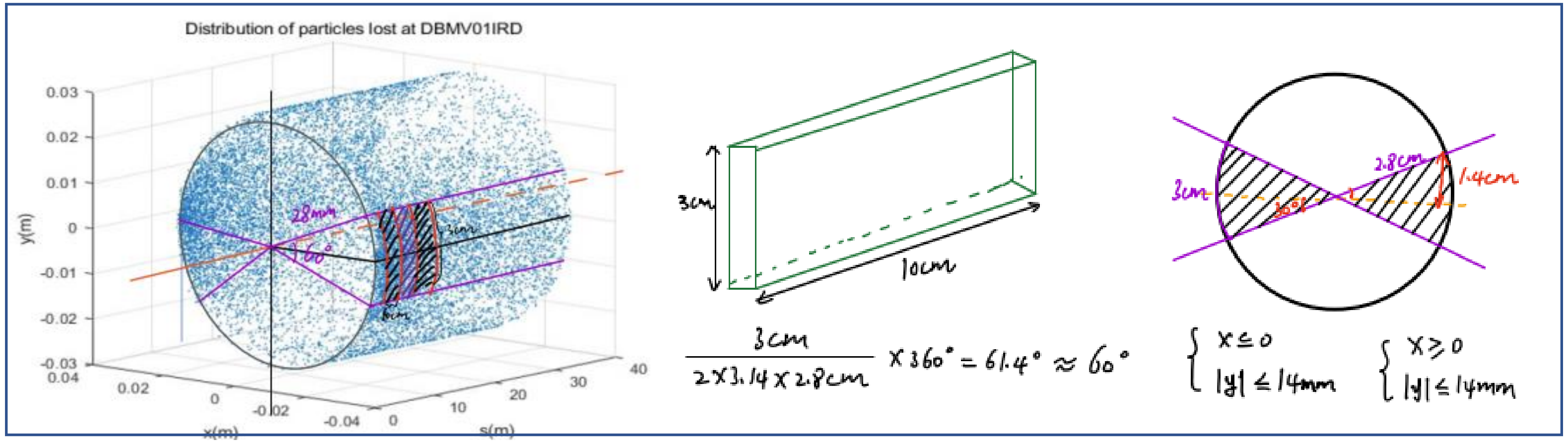


Necessity of the Fast Luminosity Monitor for CEPC

- Any Collider must have a luminosity monitor, but not necessarily a fast luminosity monitor**.** If want to do fast IP luminosity tuning and feedback, maybe should have a fast and precise luminosity monitor.

	Standard luminosity monitor(LumiCal)	**Fast luminosity monitor**
Process	Radiative Bhabha at finite angle	Radiative Bhabha at zero angle
$\boldsymbol{\sigma_{Higgs}}$	$10^{-31}cm^{-2}$	$1.27\times10^{-25}cm^{-2}$
Design goal	• precise physics measurement • slow beam tuning (@1Hz)	• Fast feedback • Tuning accelerator beam parameter at IP
characteristic	Slow but can be precisely calibrated	Faster but not easy to calibrate precisely
Luminosity	$L = 5\times10^{34}cm^{-2}s^{-1}$	
Events	$N = L\times\sigma\times T\times \mathrm{f}$	
	Assuming f = 1 $N = 0.5\times5\times10^{34}\times10^{-31}$ $= 2.5\times10^{3}/s \rightarrow \nu = 2\times10^{-2}@1Hz$ $= 2.5\times10^{2}/0.1\ s \rightarrow \nu = 6\times10^{-2}@10Hz$ $= 25/0.01s \rightarrow \nu = 0.2@100Hz$ $= 2.5/ms \rightarrow \nu = 0.6@1kHz$	Assuming f = 0.01 $N = 5\times10^{34}\times0.5\times1.27\times10^{-25}\times0.01$ $= 3.2\times10^{7}/s \rightarrow \nu = 1.8\times10^{-4}@1Hz$ $= 3.2\times10^{6}/0.1s \rightarrow \nu = 5.6\times10^{-4}@10Hz$ $= 3.2\times10^{5}/0.01s \rightarrow \nu = 1.7\times10^{-3}@100Hz$ $= 3.2\times10^{4}/ms \rightarrow \nu = 5.6\times10^{-3}@1kHz$

☐ Select a best position to place the detector



$$\frac{3cm}{2\times 3.14\times 2.8cm}\times 360° = 61.4° \approx 60°$$

$$\begin{cases} x \le 0 \\ |y| \le 14mm \end{cases} \qquad \begin{cases} x \ge 0 \\ |y| \le 14mm \end{cases}$$

$$f = \frac{N_{loss}}{N_{total}} = \frac{78}{2\times 10^5} = 4\times 10^{-4}$$

$$N = L\times\sigma\times T\times f$$
$$= 5\times 10^{34}\times 0.5\times 1.27\times 10^{-25}\times 4\times 10^{-4}\times 1s$$
$$= 1.27\times 10^{6}\ \text{per s}\rightarrow \nu = 8.9\times 10^{-4} @1Hz$$
$$= 1.27\times 10^{4}\ \text{per 10ms}\rightarrow \nu = 8.9\times 10^{-3} @100Hz$$
$$= 1.27\times 10^{3}\ per\ ms\rightarrow \nu = 2.8\times 10^{-2} @1kHz$$

s	ideal	0.1sigmax	0.5sigmax	1sigmax	1.5sigmax	2sigmax	0.1sigmay	0.5sigmay	1sigmay	1.5sigmay	2sigmay	RMS
8.3-8.4	76	80	87	74	82	63	72	74	76	74	74	6.12
8.4-8.5	102	98	83	69	63	86	99	97	88	86	52	24.96
8.5-8.6	88	80	69	85	83	84	88	95	88	64	58	14.14
8.6-8.7	**78**	**77**	**76**	**77**	**78**	**75**	**78**	**73**	**72**	**74**	**73**	**3.42**
8.7-8.8	81	82	78	84	80	91	86	79	78	71	57	9.13
8.8-8.9	87	85	72	92	94	101	86	81	84	62	61	13.59
8.9-9	76	71	97	82						73	65	17.22
9-9.1	79	85	87	95						85	78	8.85
9.1-9.2	83	81	86	96						77	62	8.60
9.2-9.3	97	81	84	70						63	59	21.88
9.3-9.4	93	99	84	85						74	64	14.46
9.4-9.5	80	89	85	82						71	62	8.07
9.5-9.6	83	85	85	75						69	48	12.37
9.6-9.7	80	85	71	86						66	76	7.77
9.7-9.8	79	77	93	80						71	53	13.07
9.8-9.9	83	85	79	79						68	63	9.61
9.9-10	77	75	73	69						61	53	10.95
10-10.1	81	83	67	72						61	31	19.96

$s = 8.6\sim 8.7m$	Ntotal	x>0	x<0	$\lvert x_+ - x_-\rvert/Ntotal$
ideal	78	39	39	0.00
0.1sigmax	77	31	46	0.19
0.5sigmax	76	29	47	0.24
1sigmax	77	39	38	0.01
1.5sigmax	78	44	34	0.13
2sigmax	75	44	31	0.17
0.1sigmay	78	39	39	0.00
0.5sigmay	73	36	37	0.01
1sigmay	72	32	40	0.11
1.5sigmay	74	27	47	0.27
2sigmay	73	32	41	0.12
RMS	3.42	6.82	5.25	0.46

- Assuming the detector is 10cm long and 3cm high and place it in the horizontal symmetrical about Y=0. In this case, the 8.6m downstream of the IP (at the first 2.4m of BDMV01IRD) is the good position for detector.
- The total particles number lost on this area is almost unaffected by beam-beam deflection. But the distribution is no longer be symmetrical. So should put a detector on both sides. The fraction of loss particles here is 4×10^{-4}, the precise could reach 3% at 1kHz.
- It is not guaranteed that every lost particle can generate a signal in the detector, the fraction is about 60-70%, so it is necessary to consider a slightly larger detector.

Evaluate the level of background

Haoyu Shi, Sha Bai

Background source	lifetime	events	Lost on BDMV01IRD	Nloss/Nevents	Nloss /s	NlossBDM /s
Bhabha at zero	40 [min]	200000	17053	8.5×10^{-2}	1.45×10^{10}	$\mathbf{1.2 \times 10^{9}}$
Beamstrahlung	40 [min]	200000	0	0	1.45×10^{10}	0
Beam-gas bremsstrahlung	486 [hour]	53896132	2034	3.8×10^{-5}	1.99×10^{7}	7.5×10^{2}
Beam-gas Coulomb	28 [hour]	552608	767	1.4×10^{-3}	3.45×10^{8}	4.8×10^{5}
Beam-thermal photon	50 [hour]	65804508	137	2×10^{-6}	1.94×10^{8}	3.9×10^{2}

- Assuming linear loss, i.e., the number of particles lost each turn is the same

$N_0 = N_p \times N_b = 1.3 \times 10^{11} \times 268 = 3.5 \times 10^{13}$ $\quad T = \frac{C}{v} = \frac{100}{3 \times 10^{5}} = 3.3 \times 10^{-4} s$ $\quad N_{loss} = N_0\left(1 - e^{-t/\tau}\right)$

- The number of lost particles due to Bhabha at zero degree in 1s : $N_{lossBha} = 3.5 \times 10^{13} \times \left(1 - e^{-1/(40\times60)}\right) = 1.45 \times 10^{10}$
- The number lost on BDMV01IRD in which: $N_{lossBDM} = 1.45 \times 10^{10} \times 0.085 = 1.2 \times 10^{9}$

- At BDMV01IRD, the radiative Bhabha at zero angle process dominates over the sum of all the other processes, can be ignored.

Necessity of the Fast Luminosity Monitor for CEPC

Used for IP orbit feedback as a back up

- All previous calculations assume that BPM can achieve design precise, and all machine parameters can reach the design values, we can put many BPMs near maximum beta position. **But if the BPM in one direction is not so precise and at the beginning of the operation, the nominal parameters will not be achieved**, the offset generated at BPM is not big enough to accurately measured with these BPMs.
- And the luminosity is at least 10 times lower than the nominal value, and the cross-section of standard luminosity monitor is not large enough, so **standard luminosity monitor also doesn't work for fast feedback**, then maybe the luminosity monitor can be alternative.

Used for beam size tuning

- Whether you do beam size tuning with beam-beam deflection or luminosity, will introduce beam-beam blow up. We should minimize beam-beam blow-up by reducing strongly beam current, maybe factor of 100, then luminosity drops to 10^{30}. And in that case, standard luminosity monitor doesn't work, you need to wait $10^4 s$.

	Standard luminosity monitor (LumiCal)	**Fast luminosity monitor**
Lower luminosity	$L = 5\times10^{33}cm^{-2}s^{-1}$ f=1 $\boldsymbol{\sigma_{Higgs}} = 10^{-31}cm^{-2}$ $N = L\times\sigma\times T\times \mathrm{f}$ $= 0.5\times5\times10^{34}\times10^{-31}\times1$ $= 2.5\times10^{2}/\mathrm{s} = 2.5/10\mathrm{ms}$ **If measure at 100Hz, the precise is 0.63**	$L = 5\times10^{33}cm^{-2}s^{-1}$ $\mathrm{f} = 0.01$ $\boldsymbol{\sigma_{Higgs}} = 1.27\times10^{-25}cm^{-2}$ $N = L\times\sigma\times T\times \mathrm{f}$ $= 5\times10^{34}\times0.5\times1.27\times10^{-25}\times0.01$ $= 3.2\times10^{6}/\mathrm{s} = 3.2\times10^{4}/10\mathrm{ms}$ **If measure at 100Hz, the precise is 5.6×10^{-3}**
Lower current	$L = 5\times10^{30}cm^{-2}s^{-1}$ $N = L\times\sigma\times T\times \mathrm{f} = 0.25/\mathrm{s}$ **If measure at 1Hz, the precise is 2**	$L = 5\times10^{30}cm^{-2}s^{-1}$ $N = L\times\sigma\times T\times \mathrm{f} = 3.2\times10^{2}/\mathrm{s}$ **If measure at 1Hz, the precise is 0.06**