Discussion about the CEPC polarimeter design

CEPC Energy Calibration Group

22 December 2021

CEPC Day, Beijing

Outline

- Discuss a suitable location of the Compton polarimeter
  - Requirements for the Compton polarimeter
  - Design of the Compton polarimeter
  - Discuss the suitable location of the detector
  - Feasibility of measurement of transverse polarization by Compton polarimeter
    - Statistical errors and statistical errors (For 10% transverse polarization)
  - Summary

- About the Compton polarimeter in the past:
  - CEPC Physics and Detector Plenary Meeting (May 12, 2021) (ihep.ac.cn)
  - CEPC Physics and Detector Plenary Meeting (August 18, 2021) (ihep.ac.cn)
  - CEPC DAY (August 30, 2021) (August 30, 2021) (ihep.ac.cn)
  - CEPC Physics and Detector Plenary Meeting (December 15, 2021) (ihep.ac.cn)

Motivation for Transverse polarization in CEPC

- Transverse polarization in an electron storage ring

Electron or positron beams naturally polarized due to the Skolov-Ternov effect.

- The maximum achievable polarization value is given by the theory as:

$$P_{max} = \frac{8}{5\sqrt{3}} \approx 92.4\%$$

- Self-Polarization build-up time

$$\tau_{BKS} = 98.66[s]\frac{\rho[m]^2 R[m]}{E[GeV]^5} \approx 256[h]$$

R is the radius of the storage ring; ρ is the average bending radius; E is the beam energy

- The use of wigglers in the storage ring, to booster the self-polarization build up.
- At least 5% ~ 10% transverse polarization, for both electron and positron beams.
- The measurement of the transverse polarization
  - Calibrate the beam energy by RDP
  - Study the CP violation
  - Study extra dimensions in indirect searches for massive gravitons

Requirement of the Compton polarimeter

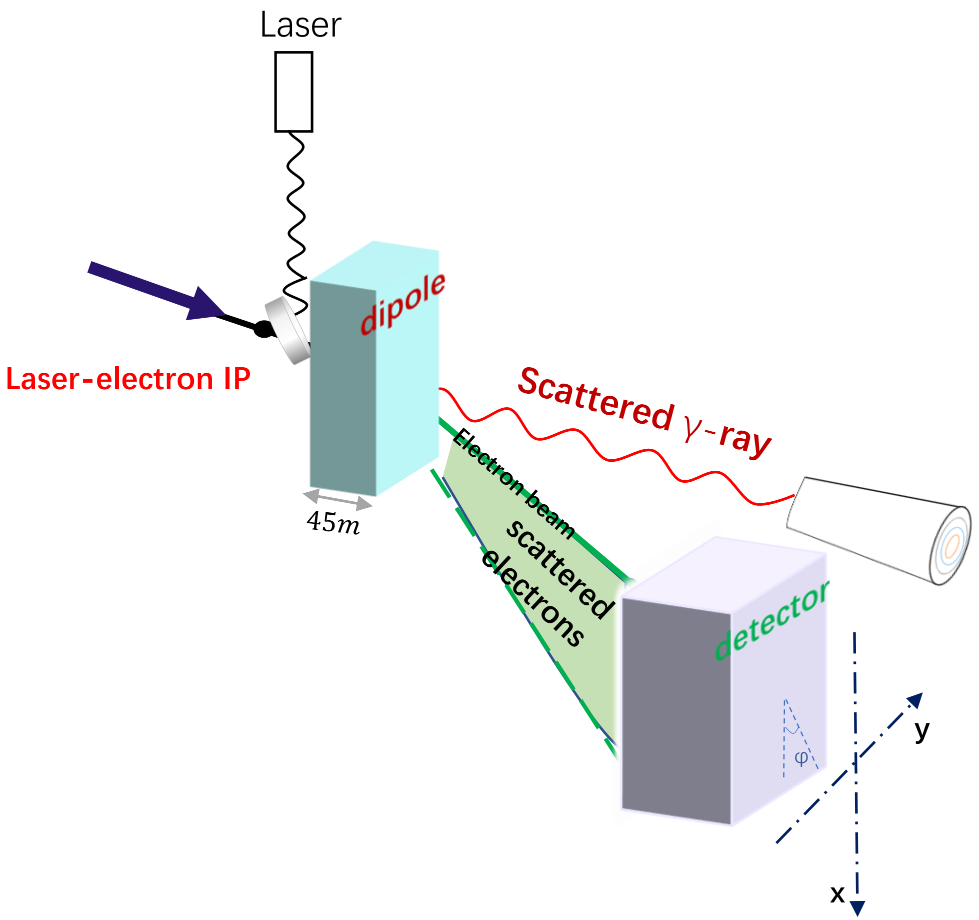


Fig. 4 Diagram of Compton polarimeter

- **Compton polarimeter requirement :**
  - Electron beam parameter: The angular divergence of the electron or positron beam ($\sigma' = \sqrt{\epsilon/\beta}$,$\epsilon$:beam emittance, β: β function)must be small in Laser-electron IP compared to typical backscattered electrons angular distribution or else the polarization information will be lost.
  - Dipole and a clear distance to separate the scattered photons and electrons from beam.
  - The location of the detector: to obtain the spatial distribution of scattered electrons.

A candidate location of the Compton polarimeter ???

➢ Optics of the interaction region for Z mode

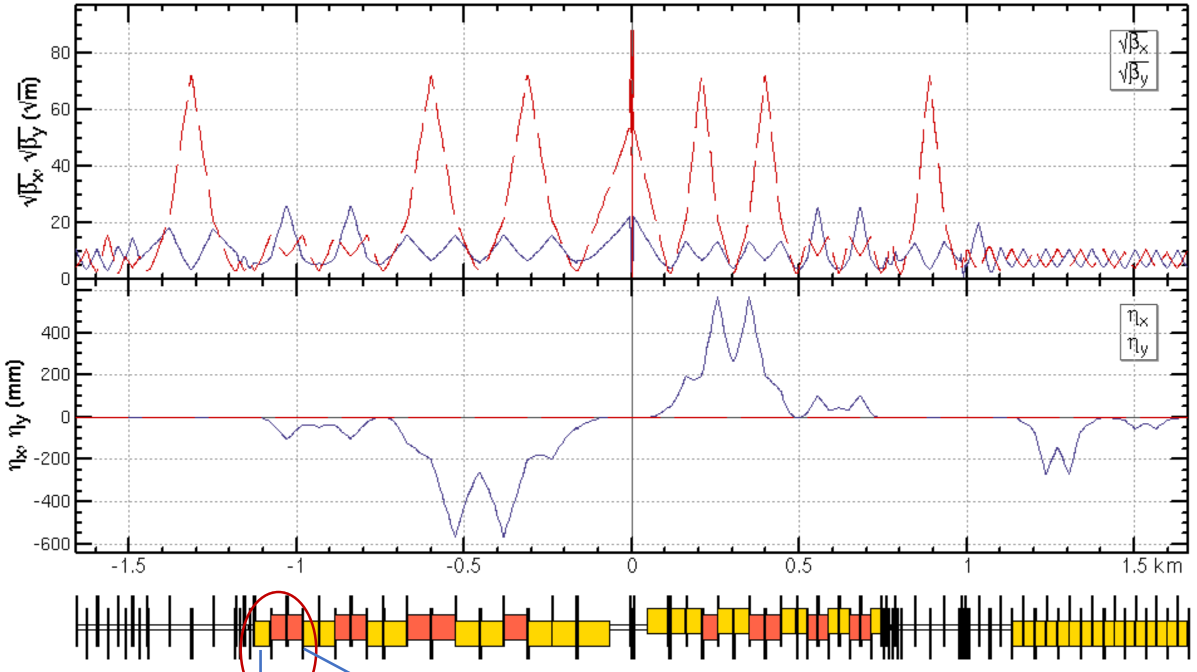


Fig.1 The lattice design and geometry of the interaction region for Z mode

About 100 meters drift length

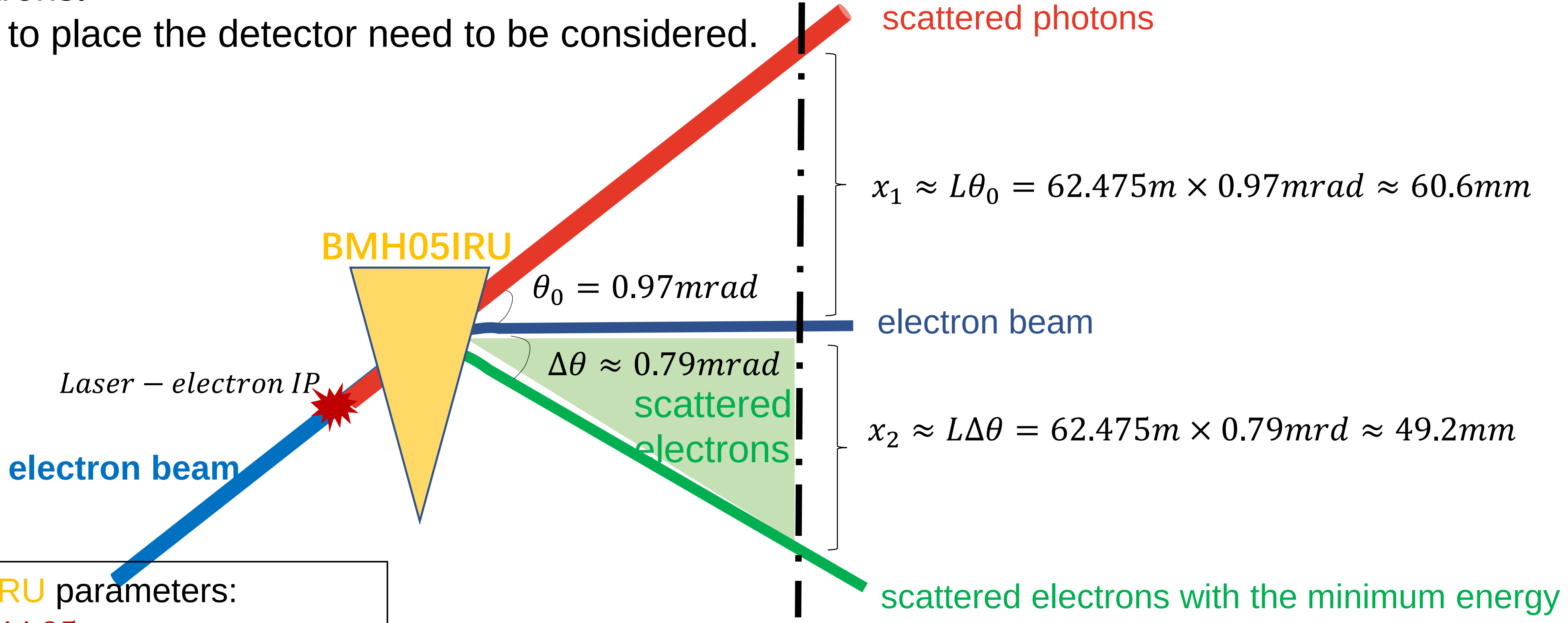
A Candidate location???

BMH05IRU

- The transverse polarimeter locate at the upstream before the e^+e^- IP region, about 1km before the e^+e^- IP.
  - Possible problem: Analysis of the influence on the physical IP need to be done with full simulation.
- Dipole *BMH05IRU* is used as polarimeter bending magnet.
- After about 100 meters of free beam drift: allow separation of the Compton scattered photons and electrons from the beam.
- Whether this position is feasible should be considered in combination with the placement scheme of the polarimeter detector.
- Laser-electron interaction point(IP) is located about 12m before the dipole *BMH05IRU.*

Compton polarimeter

- An example of estimation:
  - In this case: the detector is placed 40 meters behind the dipole:
  - Part of the scattered electrons need to be detected by the detector.
  - The transverse polarization can be measured by measuring the spatial position of the scattered electrons.
  - How to place the detector need to be considered.

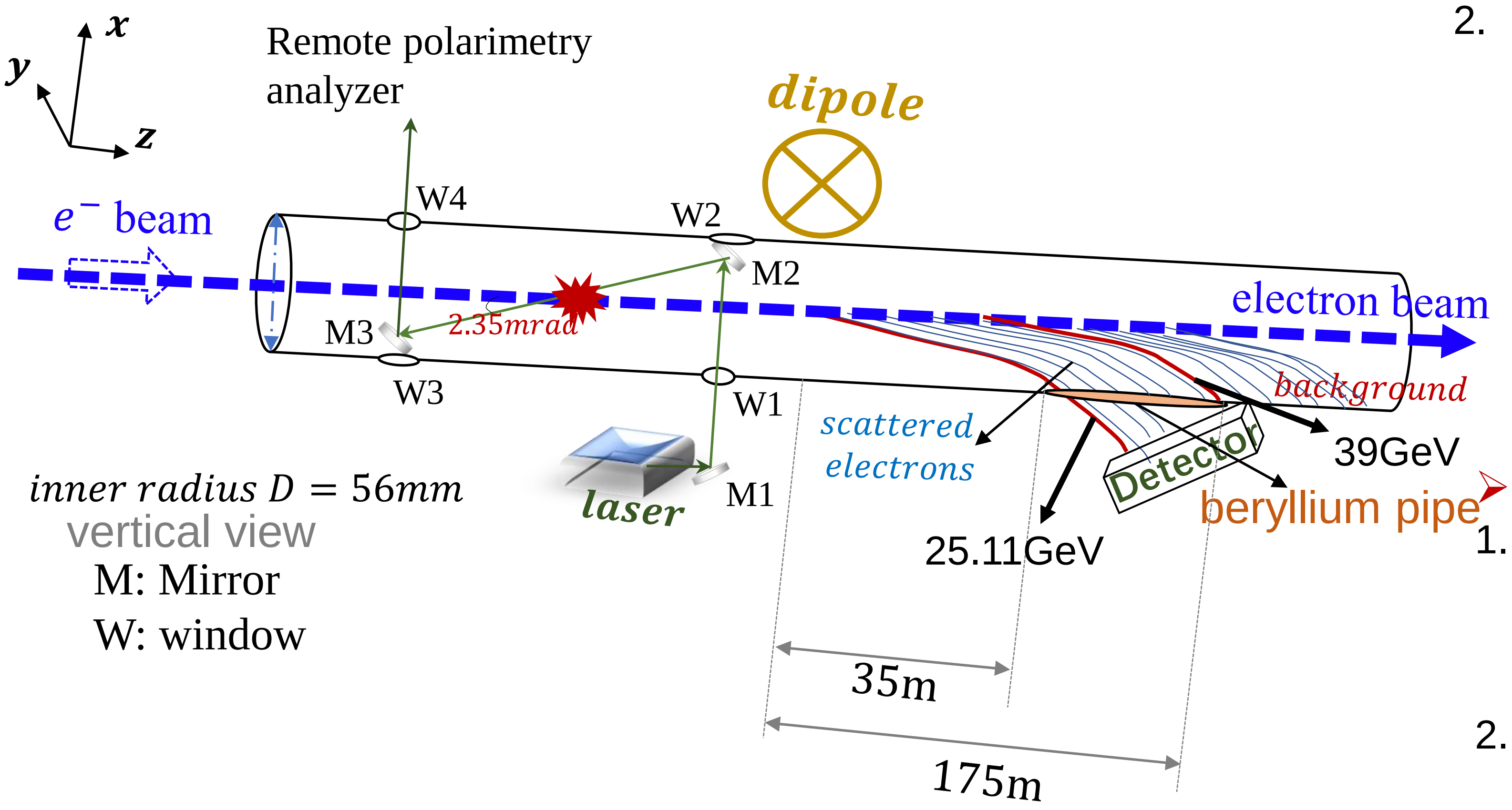


Dipole BMH05IRU parameters:
- Length: $l = 44.95m$
- Beam bending: $\theta_0 = 0.97mrad$

The distance between the center of the dipole and detector is about 62.475m

Discussion about the position of the detector

➤ Case 1: The detector is located outside the beam tube



inner radius D = 56mm

vertical view

M: Mirror

W: window

➤ Some Modifications to the lattice layout:

1. Fine focusing adjustment can be performed by the remotely movable mirror system.
2. The beam tube needs to be beryllium pipe to make scattered electrons exit the tube: the scattered electrons (25.11GeV~39GeV) is accepted by detector, the angle between the scattered electrons and the main beam is 0.16mrad~0.79mrad respectively, which corresponding to 35m~175m drift distance to exit the beam tube. So the beryllium pipe may be need to be >100 meters long.

➤ The possible problem to the Physical IP:

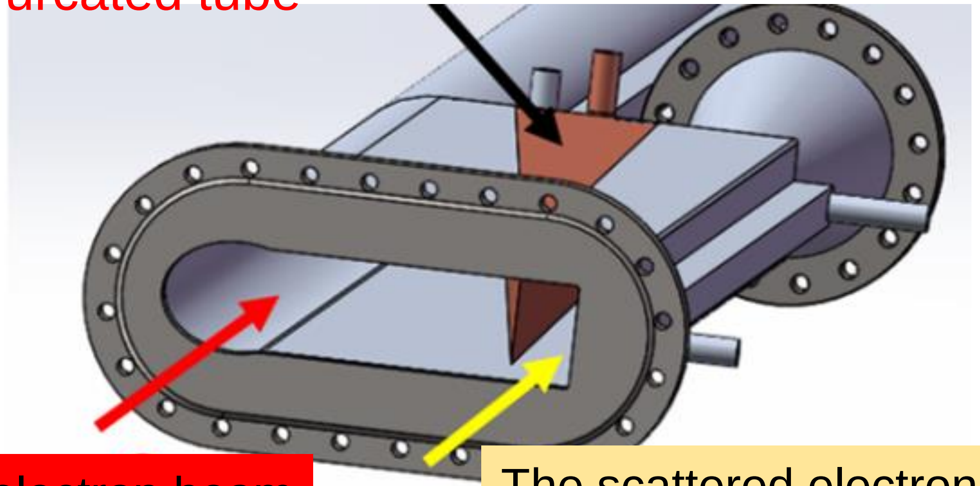
1. The beam loss problem: The scattered electron beams hitting on the surface of the beam tube are as background, which need to be evaluated.
2. The part passing through the detector will be the environmental background

➤ For Compton polarimeter:

1. The changed distribution of scattered electrons needs to be simulated.
2. Bremsstrahlung need to be considered.

Discussion about the position of the detector

- Case 2: (真空管分叉) Detector is located before the bifurcated tube
- Case 3: (真空管分叉) Detector is located behind the bifurcated tube



- Possible problems with the lattice layout:

1. Need long distance to separate the scattered electrons form the electron beam. (For scattered electron beam with 39GeV, the drift distance is 175m) ➡ A suitable position in CEPC collider ring can be modified is needed to satisfy the reqirement
2. The beam tube need to be expanded.
3. Influence the beam impedance and other lattice parameter.

- For Physical IP & Compton polarimeter:

1. Bremsstrahlung due to hitting the tube surface or the bifurcation region is complicated to evaluate.

The Feasibility of measuring transverse polarization by Compton polarimeter

- For 10% transverse polarization, the statistical error and statistical error

Compton polarimeter: Laser

- The luminosity for continuous wave(CW) laser

Electron parameter(Z-pole)	
Beam energy	E = 45.5 GeV
Bunch current	461mA
electrons number/bunch	8×10^{10}
Bunch number	12000
Bunch length σ_z	8.5mm (28ps)
Laser-electron IP β function	$\beta_x = 16.6895[m]$
	$\beta_y = 39.539[m]$
Laser-electron IP Beam size	$\sigma_x = 0.0543$ [mm]
	$\sigma_y = 0.0079$ [mm]

laser parameter	
Operated on continuous wave mode	
Average power	5 [W]
wavelength	1064[nm]
Waist size	$\sigma_0 = 300$ [μm]
Rayleigh length	$z_R = \frac{\pi\sigma_0^2}{\lambda} = 26.5$ [cm]

- The luminosity for continuous wave(CW) laser

$$\mathcal{L}_{CW} = \frac{(1+cos\alpha)}{sin\alpha}\frac{I_e}{e}\frac{P_L\lambda}{hc^2}\frac{1}{\sqrt{\sigma_{e,y}^2+\sigma_{\gamma,y}^2}}\frac{1}{\sqrt{2\pi}} = 2.91 \times 10^{35} m^{-2}\cdot s^{-1}$$

- The cross section of Compton scattering

$$\sigma_{total} = \frac{2\pi r_e^2}{\kappa}\left[\left(1-\frac{4}{\kappa}-\frac{8}{\kappa^2}\right)\log(1+\kappa)+\frac{1}{2}\left(1-\frac{1}{(1+\kappa)^2}\right)+\frac{8}{\kappa}\right] = 402mb$$

- The scattering rates for per collision

$$N = \mathcal{L}_{CW}\sigma = 2.91 \times 10^{35} m^{-2}\cdot s^{-1} \times 402mb \approx 1.17 \times 10^7$$

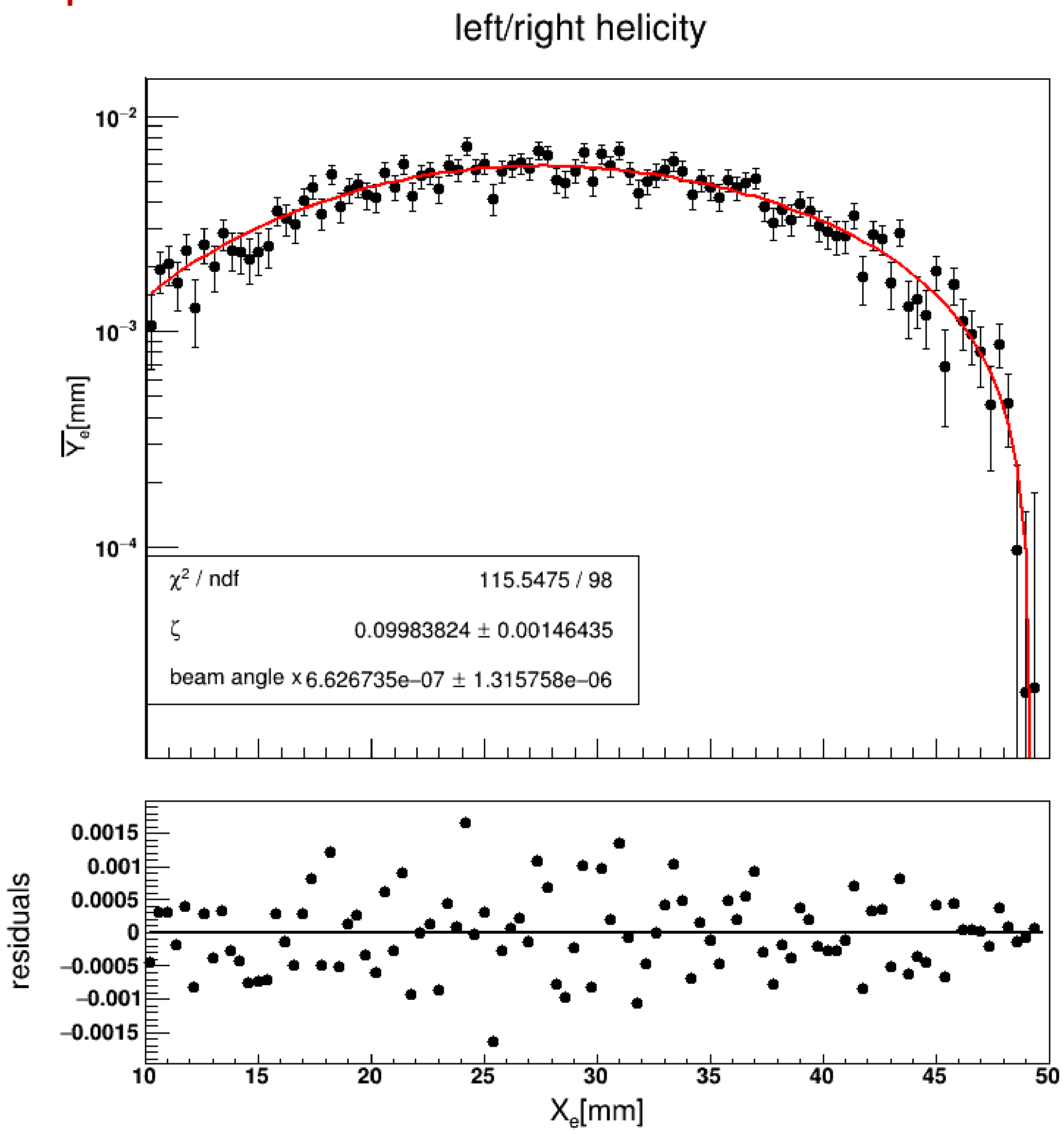
For 10% transverse polarization

◆ Case: the detector is placed 40 meters behind the dipole:

- **Detector design:**

  Active area: X*Y = 40mm*1.5mm;
  Pixel size: 400μm*25μm
  (pixel Y is important !!!)

- The relative statistical error for 10% polarization
  In one collision (1s), the relative statistical error is about $\frac{\Delta P}{P} \approx \frac{0.001464}{0.099838} \approx 1.47\%$



Conclusion :
- The absolute statistical error is the same for the same statistics;
- The relative statistical error is different for different polarization.

Systematic uncertainties(10% transverse polarization)

Sources of systematic error	Uncertainty	$\Delta P_{\perp}/P_{\perp}$ [%]
Dipole strength ($B = 3.273 \times 10^{-3} T$)	$\delta B = \frac{B}{10000} = 3.273 \times 10^{-7} T$	0.029%
L_1 (Ip to detector) ($L_1 = 96.95$m)	$\delta L_1 = 1cm$	0.0062%
L_2 (Dipole to detector) ($L_2 = 62.475$m)	$\delta L_2 = 1cm$	0.152%
Energy spread (E = 45.5GeV)	$\delta E_{beam} = 0.08\% E_{beam} = 36.4 MeV$	0.022%
Detector resolution	Pixel size: $400\mu m \times 25\mu m$ Position Resolution : $115\mu m \times 7.22\mu m$	0.923%
Laser-electron Cross angle α (α = 2.35mrad)	$\Delta\alpha$ = 1mrad	Neglected ($\rightarrow \Delta X_e \approx 10^{-9} m \ll$ detector resolution)
Detector placement deviation	Vertical/horizontal deviation angle ~ 1mrad	Neglected ($\rightarrow \Delta X_e/\Delta Y_e \approx 2.5 \times 10^{-8} m \ll$ detector resolution)
Total		**1.1322%**

- The background source from the upstream are not considered and will be simulated and evaluated later.

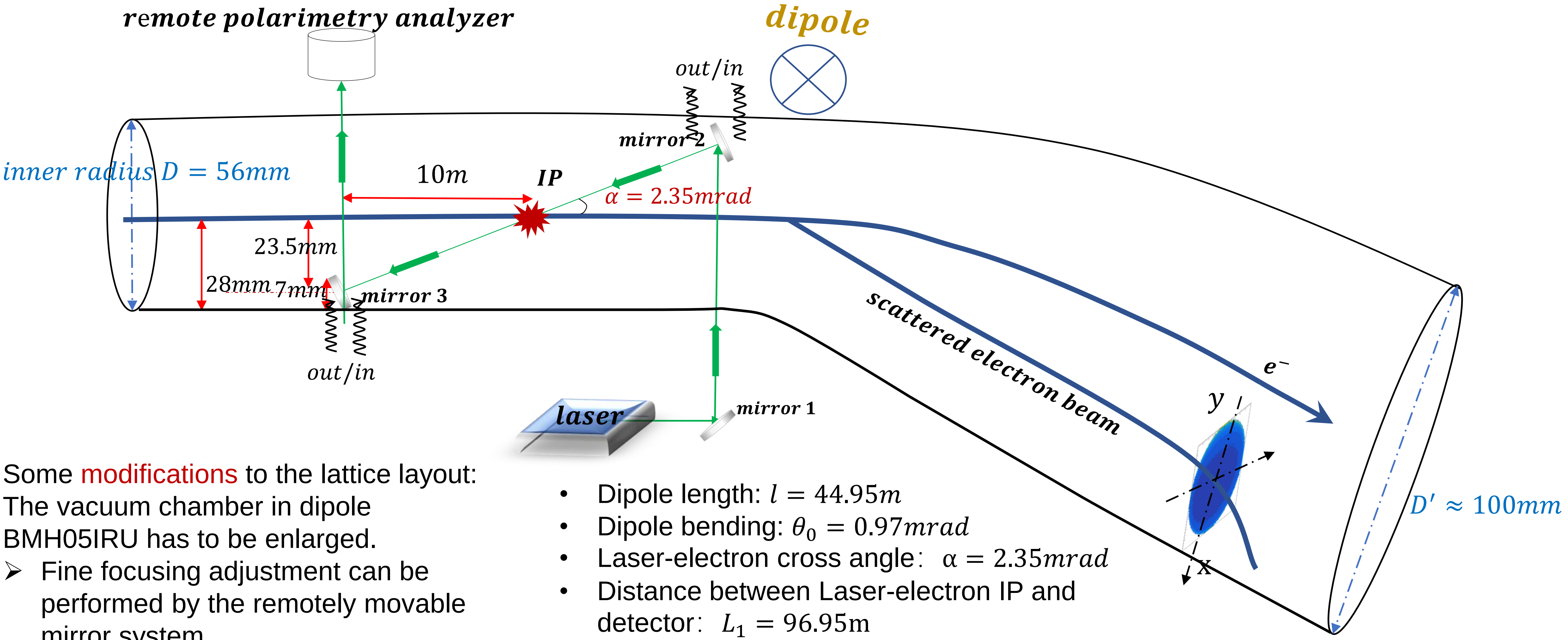
Discussion

- Compton polarimeter requirement :
    - Electron parameter: The angular divergence of the electron or positron beam must be small in Laser-electron IP compared to typical backscattered electrons angular distribution or else the polarization information will be lost.
    - Dipole and a clear distance to separate the scattered photons and electrons from beam.
    - The arrangement of the detector: to obtain the spatial distribution of scattered electrons.
- Considering the lattice design and the possible background on physics IP, as well as the requirements of Compton polarimeter: to discuss the suitable location of the polarimeter and the detector design.
- The technical details about the scheme of detector location that need to be discussed and evaluated later.

backup

Discussion about the position of the detector

➢ Case 3: Enlarge the beam tube



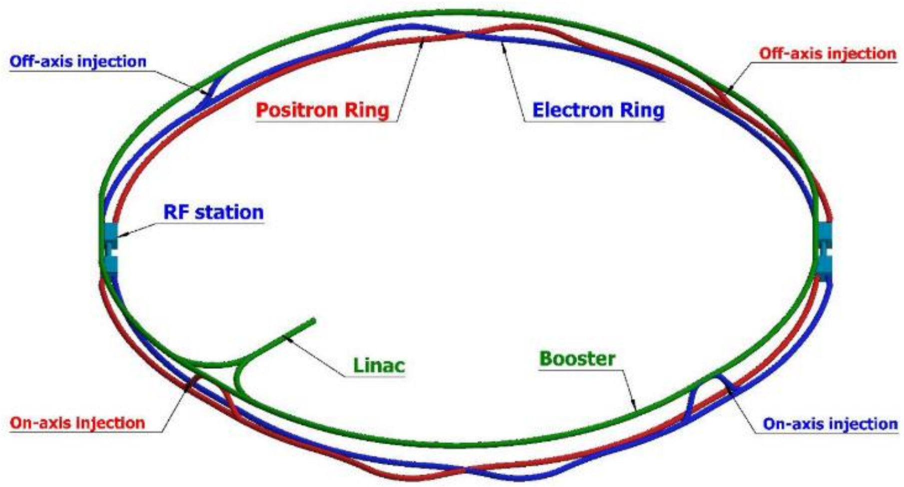
Some modifications to the lattice layout: The vacuum chamber in dipole BMH05IRU has to be enlarged.

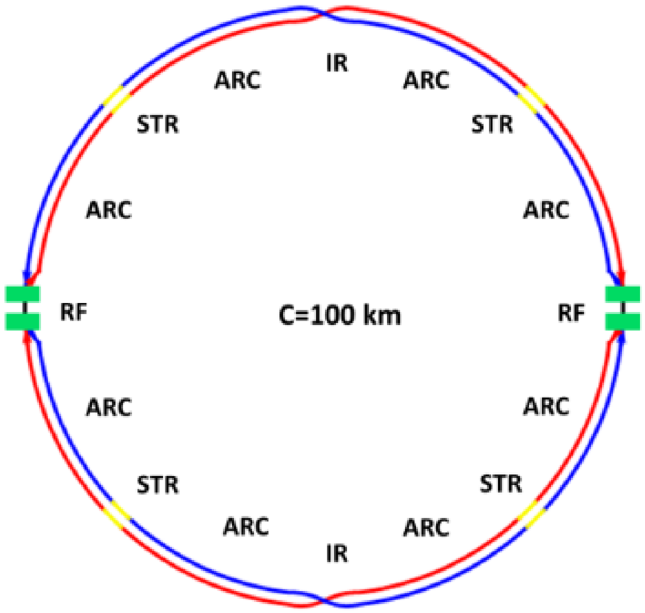
➢ Fine focusing adjustment can be performed by the remotely movable mirror system.

Possible problem: impedance

- Dipole length: $l = 44.95m$
- Dipole bending: $\theta_0 = 0.97mrad$
- Laser-electron cross angle： $\alpha = 2.35mrad$
- Distance between Laser-electron IP and detector： $L_1 = 96.95\text{m}$
- Distance between the center of the Dipole and detector： $L_2 = 62.475\text{m}$

CEPC layout





CEPC layout:

- 8 straight sections in the Collider: 2 interaction regions, 2 RF regions and 4 injection regions.
- Among them, two off-axis injection regions are for Higgs, W and Z modes
- The two on-axis injection regions are used only for Higgs mode

Ref : 王毅伟

name	Length[m]	x[m]	y[m]	theta[mrad]	sigmax[mm]	sigmay[mm]	bx[m]	by[m]
MTMP	0	0	0	0	0.1051	0.0046	62.6063	13.6096
DRCM1IRU.1	0.5	0	0	0	0.1051	0.0046	62.6063	13.6096
QCM4IRU	3	0.5	0	0	0.1069	0.0045	64.7419	12.746
DRCM0IRU.1	0.5012	3.5	0	0	0.1113	0.004	70.1981	10.152
DRCM0IRU.2	0.5012	4.0012	0	0	0.111	0.004	69.7914	10.1091
QCM3IRU	3	4.5023	0	0	0.1107	0.004	69.393	10.116
DRCMIRU.1	8.3192	7.5023	0	0	0.1022	0.0044	59.1342	12.5528
DBMCIRU	0.5	15.8216	0	0	0.0624	0.0074	22.0521	35.2602
DRCM1IRU.2	0.5	16.3216	0	0	0.0602	0.0076	20.5182	37.2089
QCM2IRU	3	16.8216	0	0	0.058	0.0078	19.0632	39.2238
DRCMIRU.2	**8.3192**	**19.8216**	**0**	**0**	**0.0543**	**0.0079**	**16.6895**	**39.539**
BMC1IRU	***0.5***	28.1408	0	0	0.0742	0.0049	31.1607	15.4631
DRCM1IRU.3	***0.5***	28.6408	0	-1.00E-04	0.0756	0.0048	32.3735	14.5533
QCM1IRU	***3***	29.1408	0	-1.00E-04	0.077	0.0046	33.6252	13.7045
DRCM0AIRU	***0.4511***	32.1408	0	-1.00E-04	0.0814	0.0042	37.5532	11.2117
DSADDHIRU.1	***0.05***	32.5919	0	-1.00E-04	0.0814	0.0042	37.5466	11.1894
MCRABIRU	***0***	32.6419	0	-1.00E-04	0.0814	0.0042	37.5465	11.1892
DSADDHIRU.2	***0.05***	32.6419	0	-1.00E-04	0.0814	0.0042	37.5465	11.1892
DRH0AIRU	***1***	32.6919	0	-1.00E-04	0.0814	0.0042	37.5466	11.1894
QFHH8IRU	***0.5***	33.6919	0	-1.00E-04	0.0814	0.0042	37.5759	11.2877
DRH1IRU.1	***0.5***	34.1919	0	-1.00E-04	0.0812	0.0042	37.3277	11.4898
BMH05IRU	**44.95**	34.6919	0	-1.00E-04	0.0806	0.0043	36.8131	11.8249
DRH1IRU.2	0.5	79.6419	-0.0218	**-0.9701**	0.1031	0.0193	60.2582	236.9926
QDH4IRU	1	80.1419	-0.0223	-0.9701	0.104	0.0195	61.2945	241.6668
DRH1IRU.3	0.5	81.1419	-0.0233	-0.9701	0.1074	0.0196	65.3081	243.8295
BMH04IRU	**44.95**	81.6419	-0.0237	-0.9701	0.1098	0.0195	68.3553	241.2804
DRH1IRU.4	0.5	126.5918	-0.0674	-0.9701	0.3405	0.0109	656.76	75.2698
QFHH7IRU	0.5	127.0918	-0.0678	-0.9701	0.3431	0.0108	666.803	74.1256
DRHSIRU.1	0.3	127.5918	-0.0683	-0.9701	0.3444	0.0107	671.8557	73.5518
HSC2IRU.1	0.3	127.8918	-0.0686	-0.9701	0.3444	0.0107	671.8549	73.5444
DRHSIRU.2	0.3	128.1918	-0.0689	-0.9701	0.3444	0.0107	671.8543	73.5395
HS2IRU	0.3	128.4918	-0.0692	-0.9701	0.3444	0.0107	671.854	73.5371
DRHSIRU.3	0.3	128.7918	-0.0695	-0.9701	0.3444	0.0107	671.854	73.5371
HSC2IRU.2	0.3	129.0918	-0.0698	-0.9701	0.3444	0.0107	671.8543	73.5396
DRHSIRU.4	0.3	129.3918	-0.0701	-0.9701	0.3444	0.0107	671.8548	73.5445
QFHH6IRU	0.5	129.6918	-0.0704	-0.9701	0.3444	0.0107	671.8556	73.5518
DRH1IRU.5	0.5	130.1918	-0.0708	-0.9701	0.3431	0.0108	666.8029	74.1257
BMH4IRU	**44.95**	130.6918	-0.0713	-0.9701	0.3405	0.0109	656.7599	75.2699
DRH1IRU.6	0.5	175.6418	-0.1149	-0.9701	0.1098	0.0195	68.3545	241.2842
QDH3IRU	1	176.1418	-0.1154	-0.9701	0.1074	0.0196	65.3073	243.8333
DRH1IRU.7	0.5	177.1418	-0.1164	-0.9701	0.104	0.0195	61.2937	241.6706
$$$	0	177.6418	-0.1169	-0.9701	0.1031	0.0193	60.2575	236.9964

Compton polarimeter: Laser

➢ The luminosity for pulsed laser

Parameters	meaning	value
	Nd:YAG laser operation mode: pulsed	
λ	Wavelength	1064nm
Pulsed repetition frequency	10 laser pulses are emitted in one second.	1Hz
P_L	Peak power = Laser energy / pulsed width	0.1GW
E_{laser}	Laser energy	2.8mJ
Pulsed width	duration of one laser pulse per shot or the duration of one laser pulse	28ps
σ_γ	Rms beam size	$\sigma_\gamma = 100\mu m$

For a pulsed laser, the γe luminosity is given by:

$$\mathcal{L} = N_e N_\gamma f \frac{\cos(\alpha/2)}{2\pi} \frac{1}{\sqrt{(\sigma_{e,y}^2 + \sigma_{\gamma,y}^2)}\sqrt{(\sigma_{\gamma,x}^2 + \sigma_{e,x}^2)cos^2\left(\frac{\alpha}{2}\right) + (\sigma_{\gamma,z}^2 + \sigma_{e,z}^2)sin^2\left(\frac{\alpha}{2}\right)}}$$

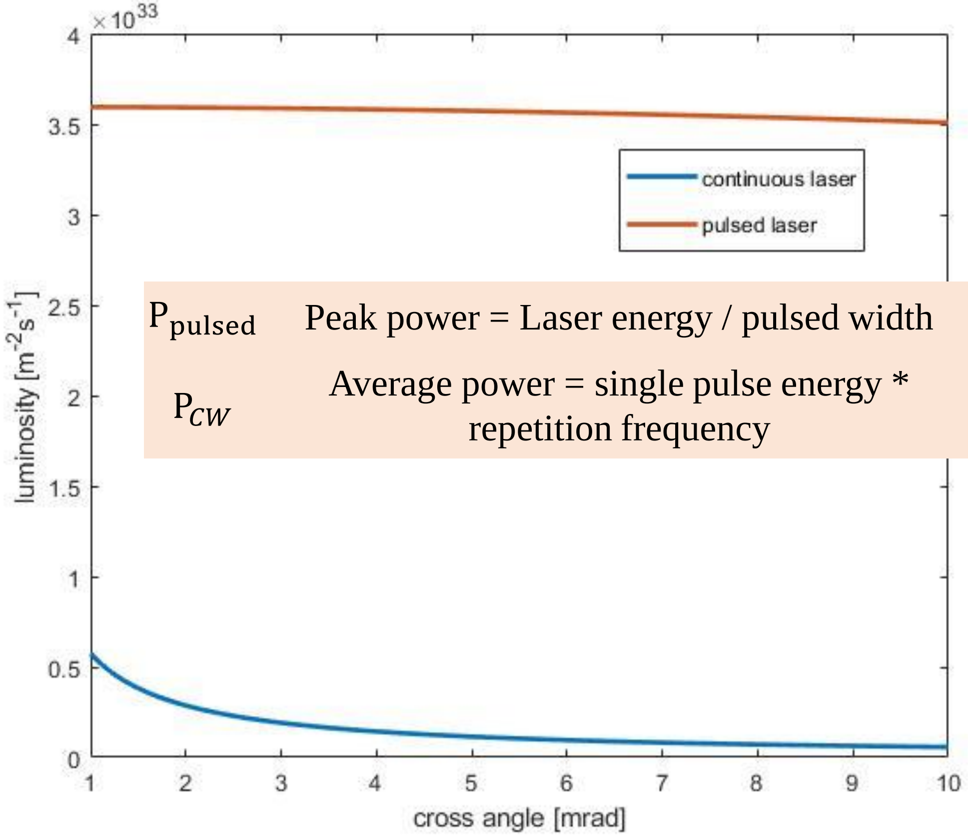
N_e — number of electrons per bunch， N_γ — number of photons per laser pulse
f — number of bunch crossing per second， α — cross angle of laser and electron (2.35mrad)
σ_e and σ_γ is the horizontal size of electron and laser

Luminosity comparisons

- Compare the continuous wave(CW) laser and pulsed laser

$$\mathcal{L}_{pulse} = N_e N_\gamma f \frac{1+\cos\alpha}{2\pi} \frac{1}{\sqrt{(\sigma_{e,y}^2+\sigma_{\gamma,y}^2)}\sqrt{(\sigma_{\gamma,x}^2+\sigma_{e,x}^2)(1+\cos\alpha)^2+(\sigma_{\gamma,z}^2+\sigma_{e,z}^2)sin^2(\alpha)}}$$

$$\mathcal{L}_{CW} = \frac{(1+cos\alpha)}{\sqrt{2\pi}} \frac{I_e}{e} \frac{P_L\lambda}{hc^2} \frac{1}{\sqrt{\sigma_{e,y}^2+\sigma_{\gamma,y}^2}} \frac{1}{sin\alpha}$$



P_{pulsed}	Peak power = Laser energy / pulsed width	0.1GW
P_{CW}	Average power = single pulse energy * repetition frequency	2.8mW

Compare Luminosity with the CW laser and pulsed laser:

- Peak Power: For CW laser, the average power is relative low. A pulsed laser has high peak power that require more protection (for mirror system or coating process).
- For the beam disturbance: scattered events per collision for CW laser is less than for pulsed laser, which corresponding to the relative large beam disturbance.
- For timing system: The requirement of timing of the laser pulse and electron bunch is high for pulsed laser, but for CW laser don't need to consider.

Compton polarimeter: Laser

- The luminosity for continuous wave(CW) laser

Electron parameter(Z-pole)	
Beam energy	E = 45.5 GeV
Bunch current	461mA
electrons number/bunch	8×10^{10}
Bunch number	12000
Bunch length σ_z	8.5mm (28ps)
Laser-electron IP β function	$\beta_x = 16.6895[m]$
	$\beta_y = 39.539[m]$
Laser-electron IP Beam size	$\sigma_x = 0.0543$ [mm]
	$\sigma_y = 0.0079$ [mm]

laser parameter	
Operated on continuous wave mode	
Average power	5 [W]
wavelength	1064[nm]
Waist size	$\sigma_0 = 300$ [μm]
Rayleigh length	$z_R = \frac{\pi\sigma_0^2}{\lambda} = 26.5$ [cm]

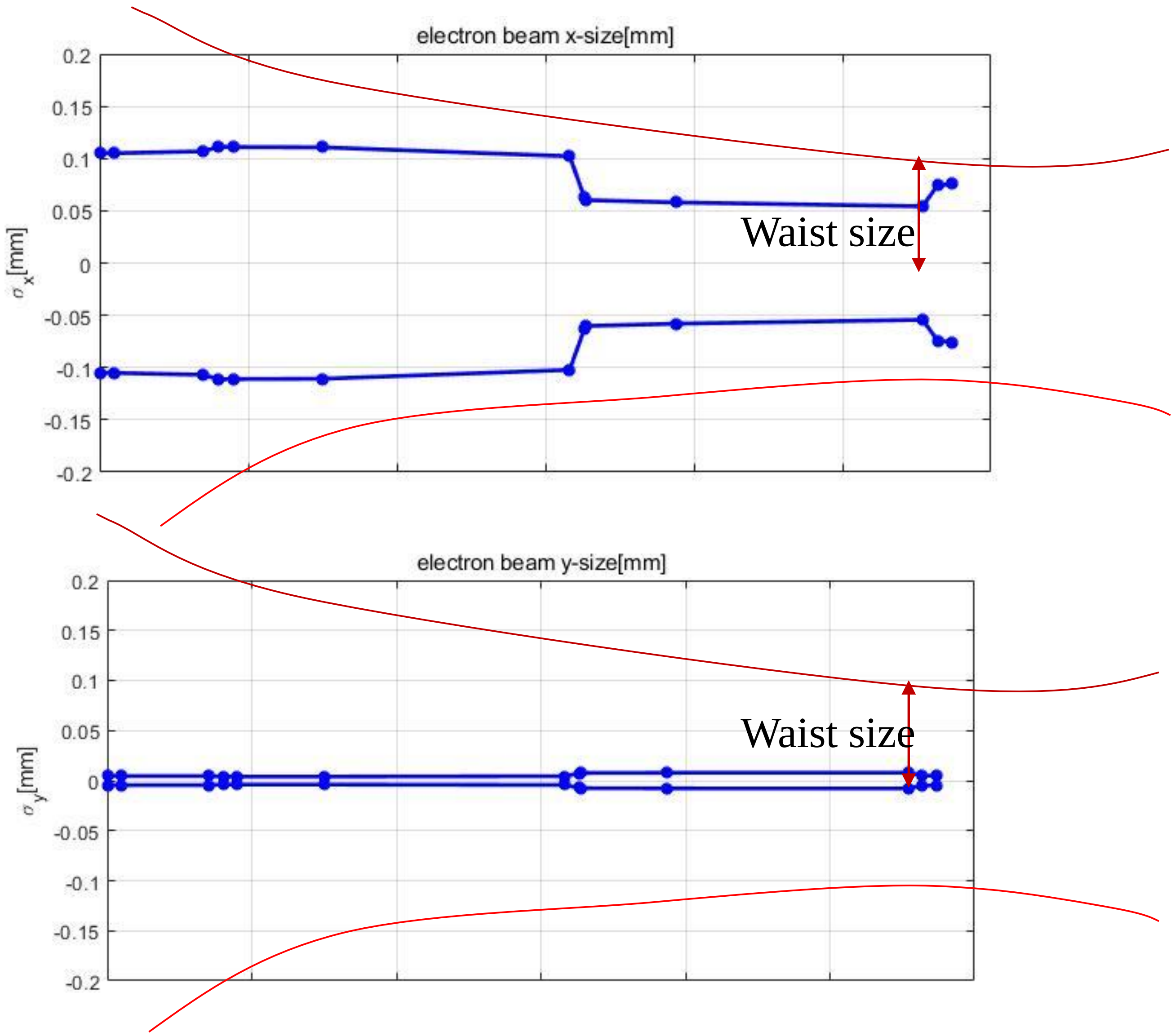
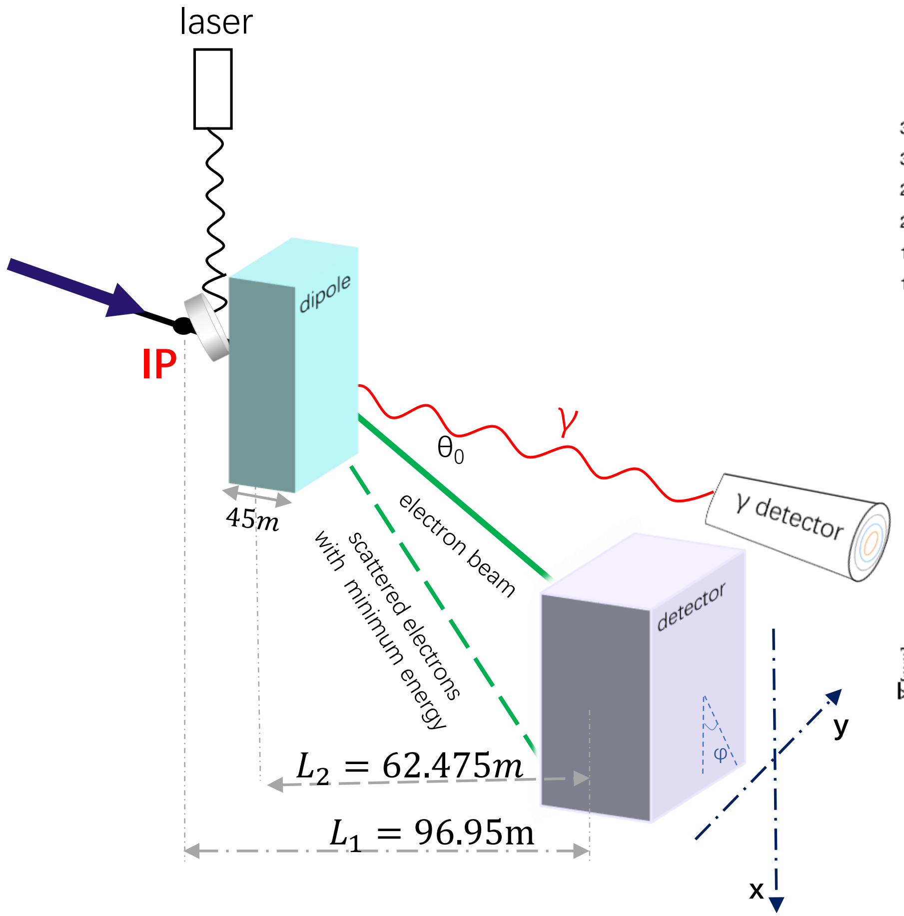


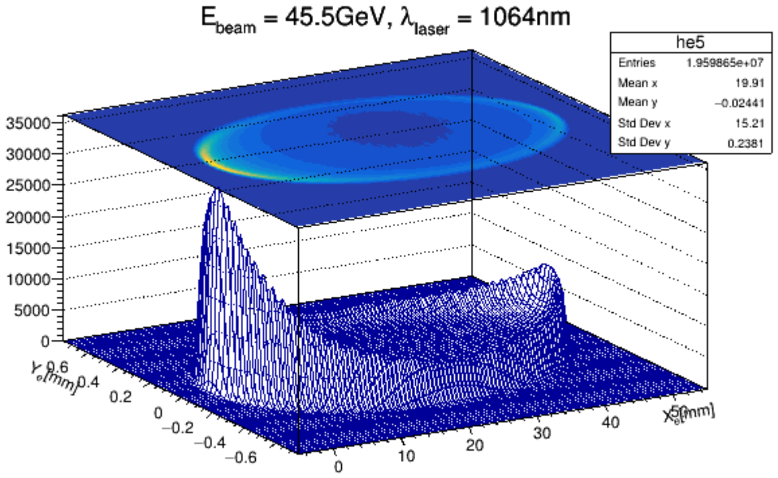
Fig. 8 Laser and electron beams size (±σ) in horizontal plane

Simulation of scattered electrons

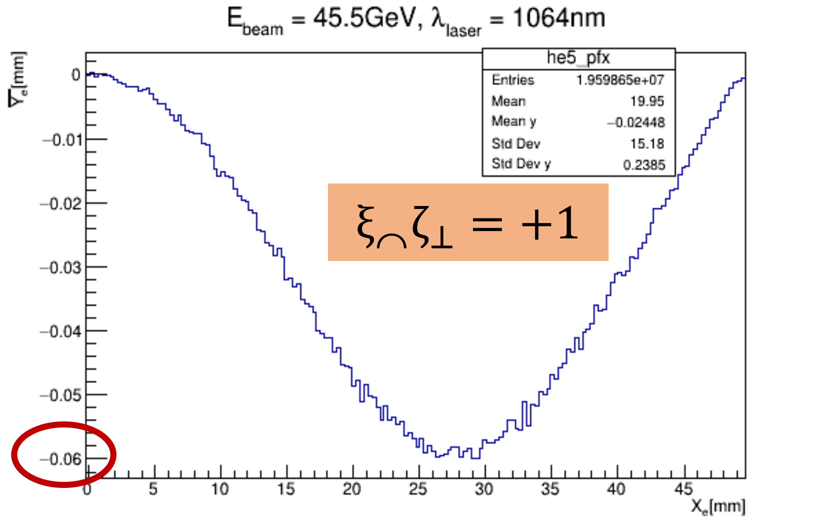
➢ The spatial distribution of scattered electron in the detector

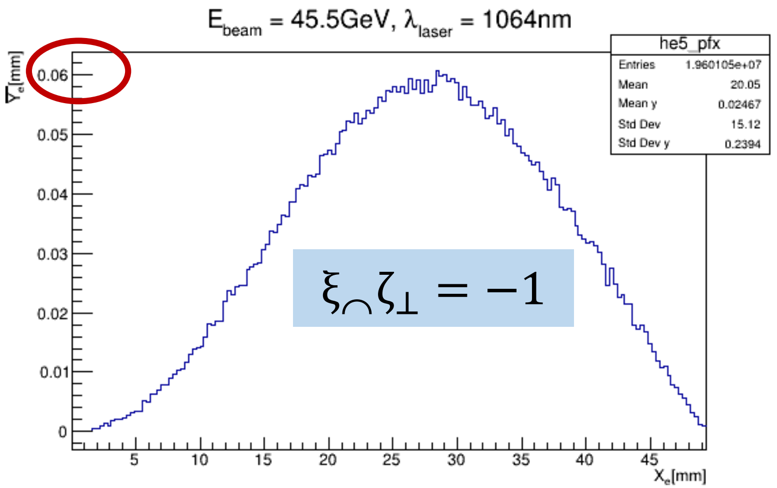
$\xi_{\frown}$ is laser circular polarization
$\zeta_{\perp}$ is electron beam transverse polarization

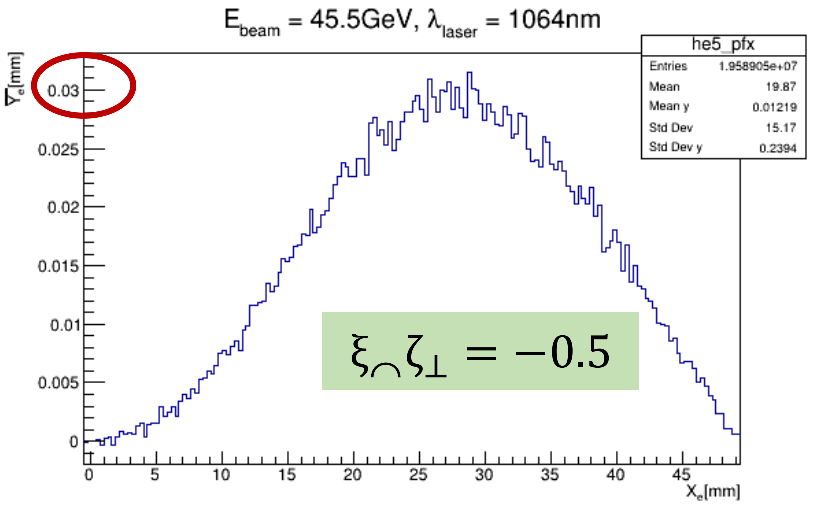




The 2D distribution of scattered electrons







- The laser of left/right helicity will cause the contrary asymmetry.
- The more polarization, the more asymmetry

Fig. 10 The Profile X of scattered electrons with different polarization

Discussion about the beam loss

Before Compton scattering	
Beam energy	45.5GeV
Laser wavelength	1064nm
After Compton scattering	
Maximum of Scattered energy of photons	20.39GeV
Minimum Scattered energy of electrons	25.11GeV

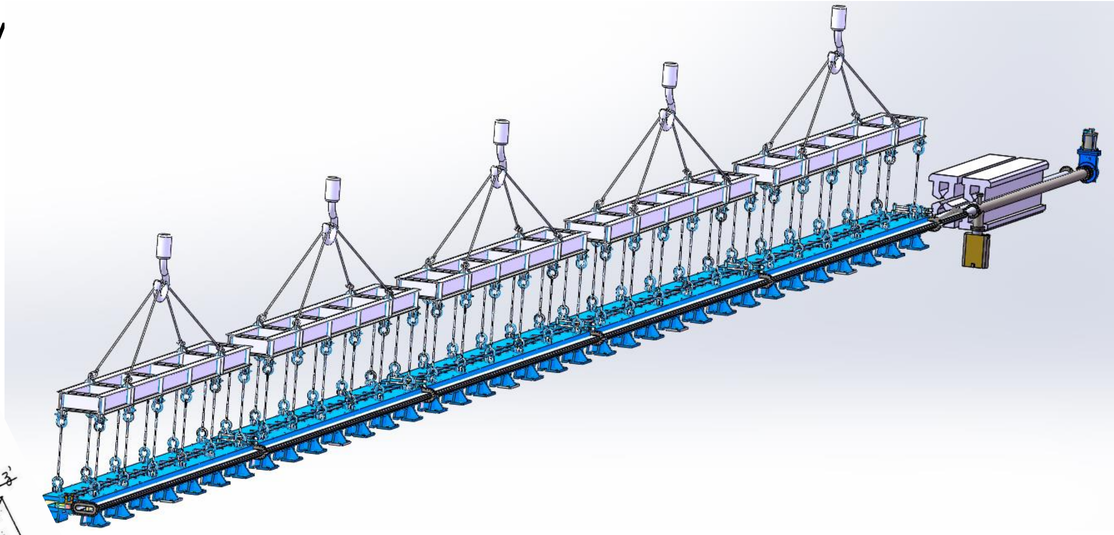
- **Detector design in polarimeter:**

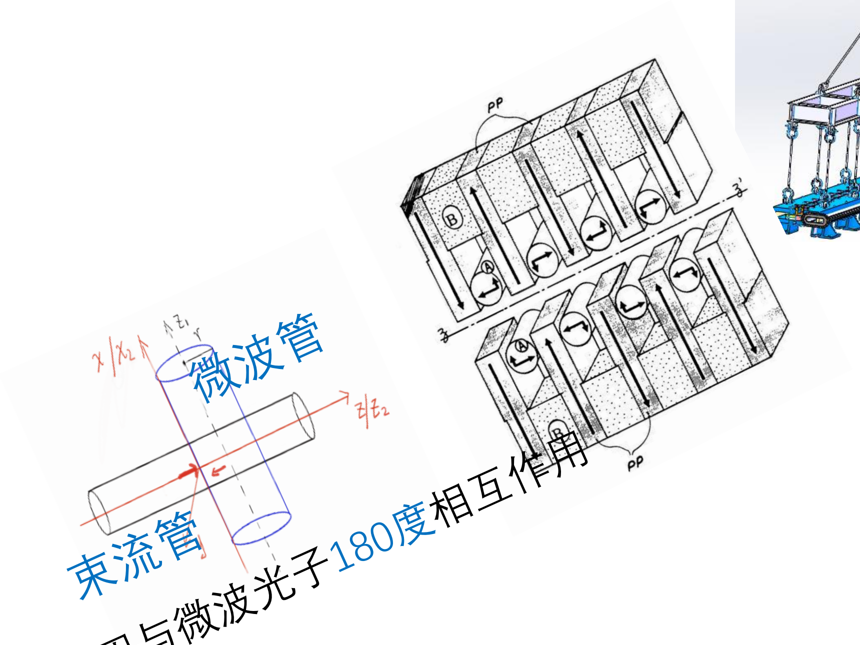
Active area: X*Y = 40mm*1.5mm;
Pixel size: 400μm*25μm
(pixel Y is important !!!)

- Considering the gap between the electron beam and scattered electrons is 10mm, that are not be accepted by the detector, which corresponding to $E \in [39GeV, 45.5GeV]$.
- Meanwhile, energy loss is large than $\pm 0.5\%(0.2275\text{GeV})$, these particles will be lost from the beam and might hit the vacuum chamber.
- Considering the Si detector acceptance, $E \in [25.11GeV, 45.2725GeV]$ belong to the beam loss, which have a clear energy spectrum distribution should be considered as the background and evaluated later.
- Meanwhile, the effect on the detector performance will be done with full simulation.

The vacuum chamber design

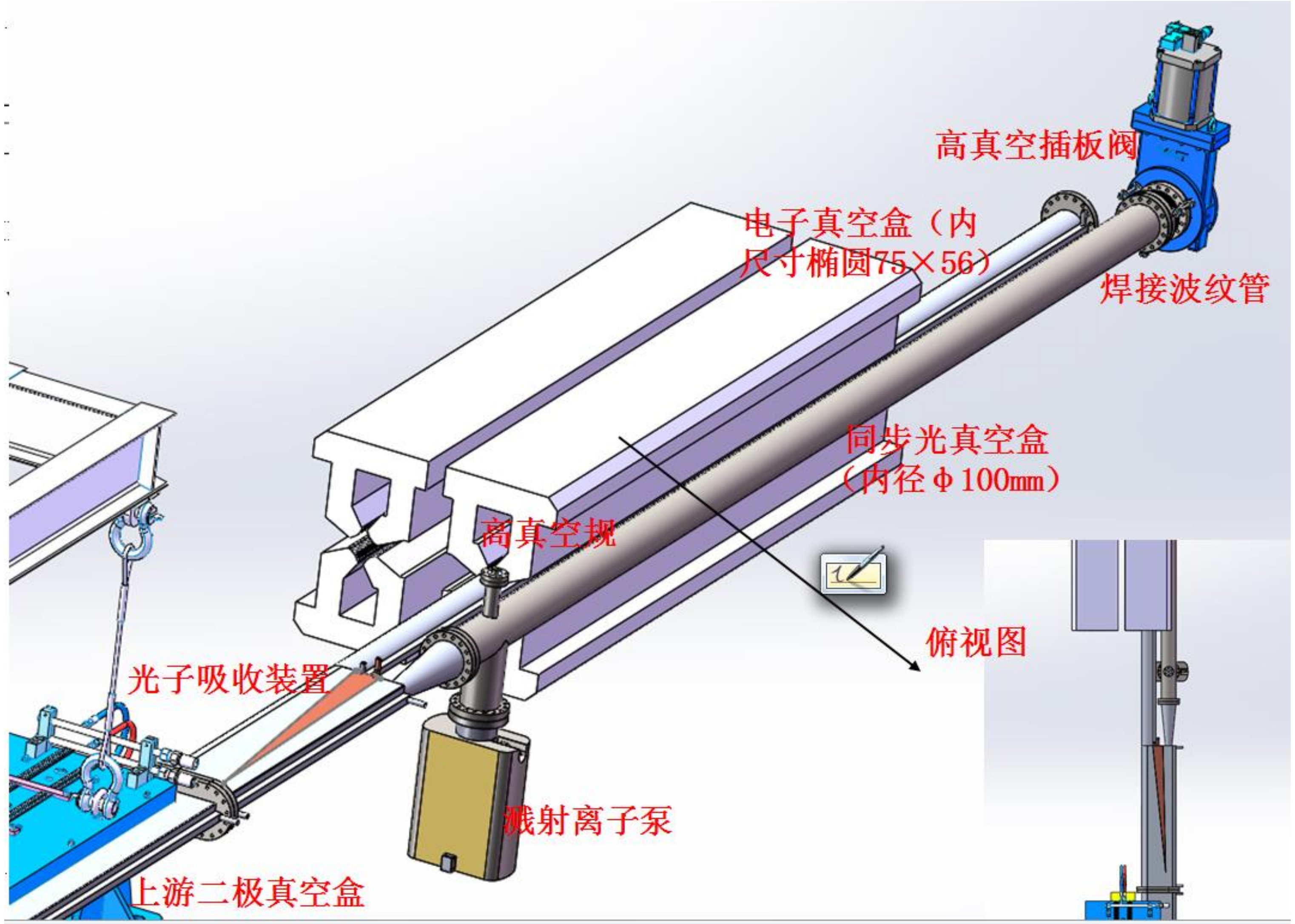
- The first diode vacuum box in the first 28-meter diode vacuum box
- The first meter diode vacuum box remains unchanged
- The second meter diode v
  150mm



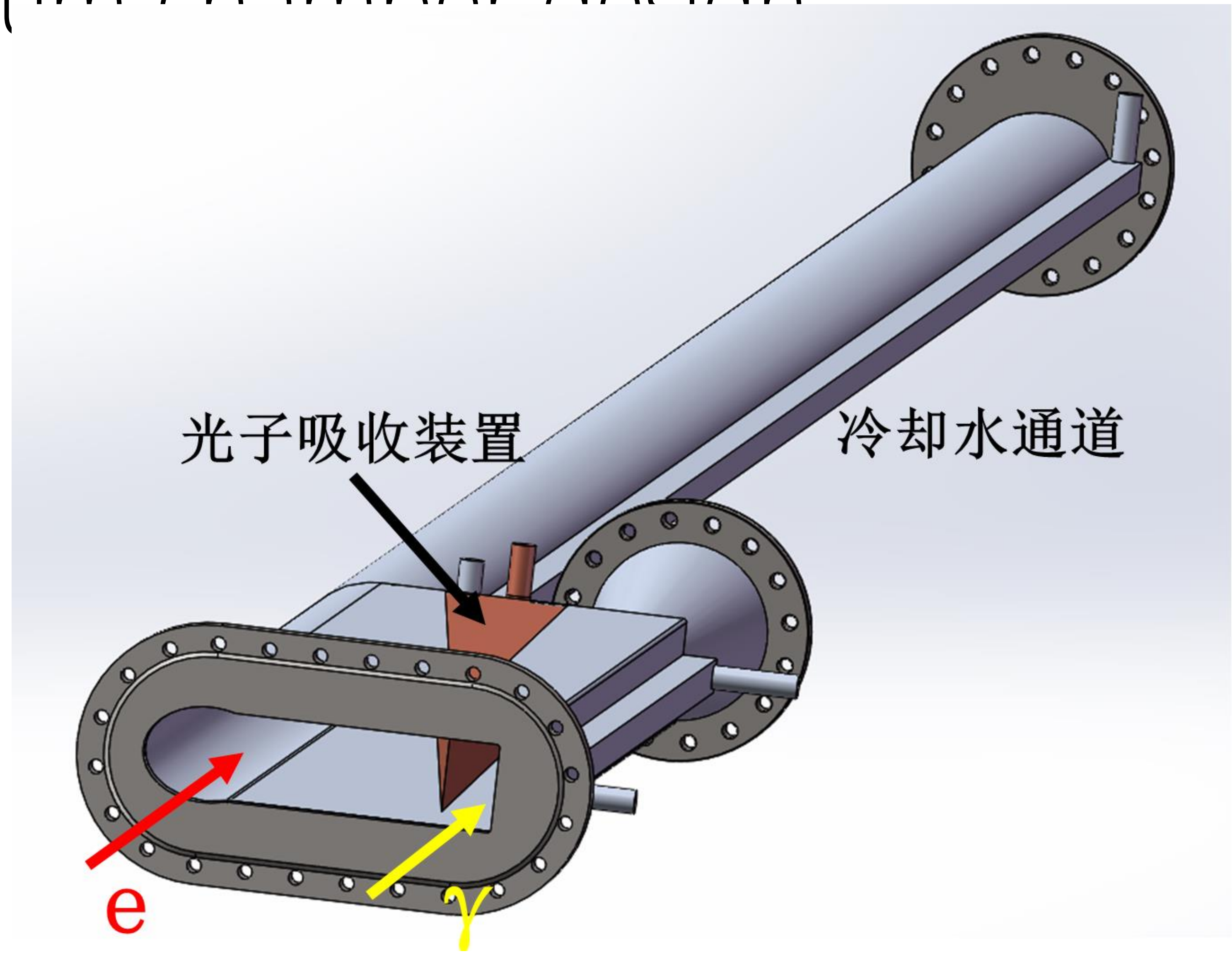


王鹏程，黄永盛，王毅伟，杨梅

真空管分叉、二级铁末端与四级铁



The vacuum chamber design



Vacuum piping in dipole iron and requirements for side ends of the iron