CEPC polarimeter design

CEPC Energy Calibration Group

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CEPC PhysDet plenary meeting, Bejing

Outline

- Discussion the implement of the Compton polarimeter setup
  - The CEPC lattice: Location of the Polarimeter
  - Design of the polarimeter
  - Design of the Laser-electron interaction region
  - Feasibility of measurement
    - Luminosity of the Laser-electron
    - Simulation of the scattered electrons
    - Measurement errors of the transverse polarization
  - Summary & Discussion

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

Require 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

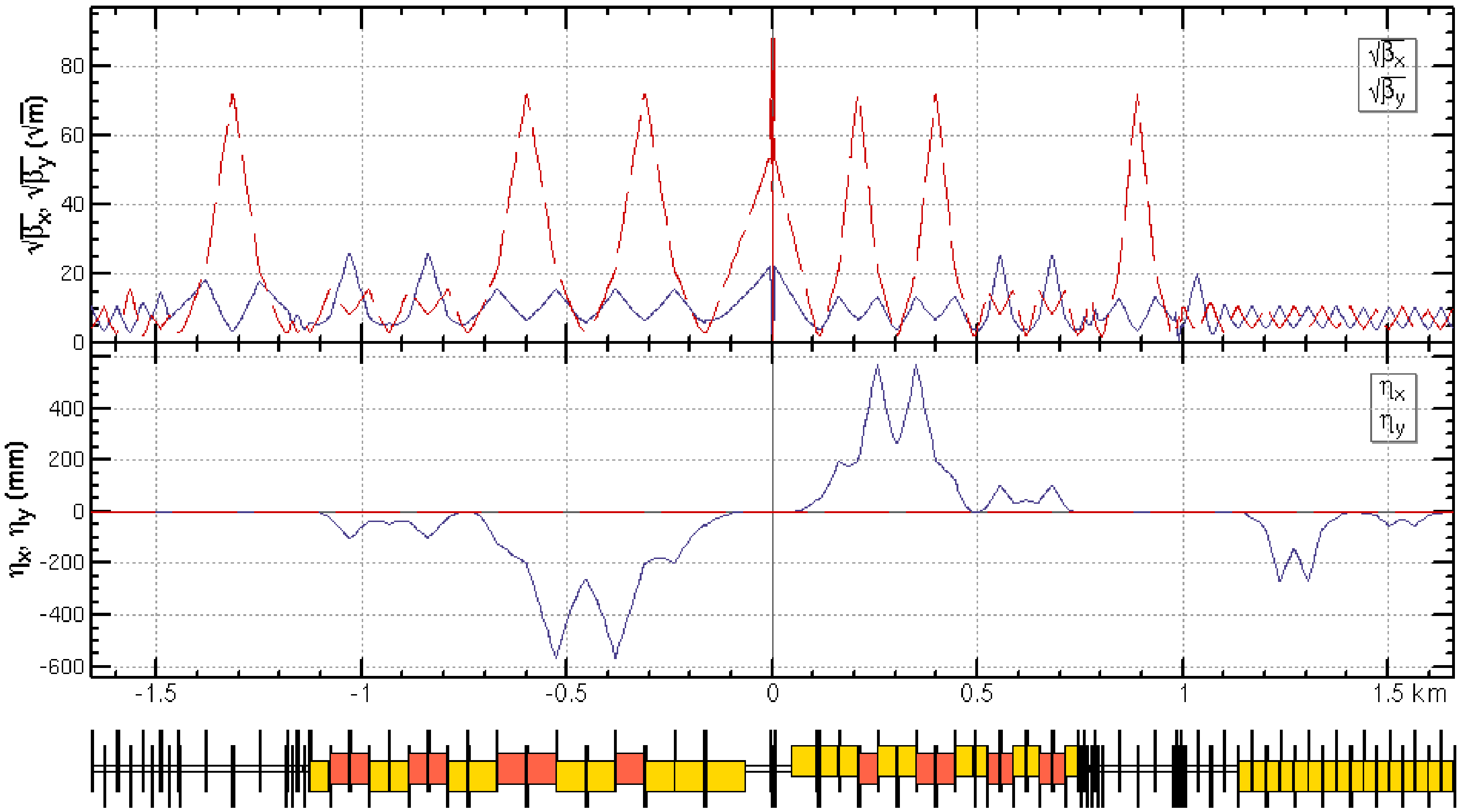
- The use of wigglers in the storage ring, to booster the self-polarization build up.
- At least 5% ~ 10% transverse polarization, for both electron and positron beams.
- The measurement of the transverse polarization
  - Calibrate the beam energy by RDP
  - Study the CP violation
  - Study extra dimensions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

Zhe duan, < CEPC Z-pole polarization > https://indico.ihep.ac.cn/event/14938/

Optics of the interaction region

➢ Z pole

Ref : 王毅伟

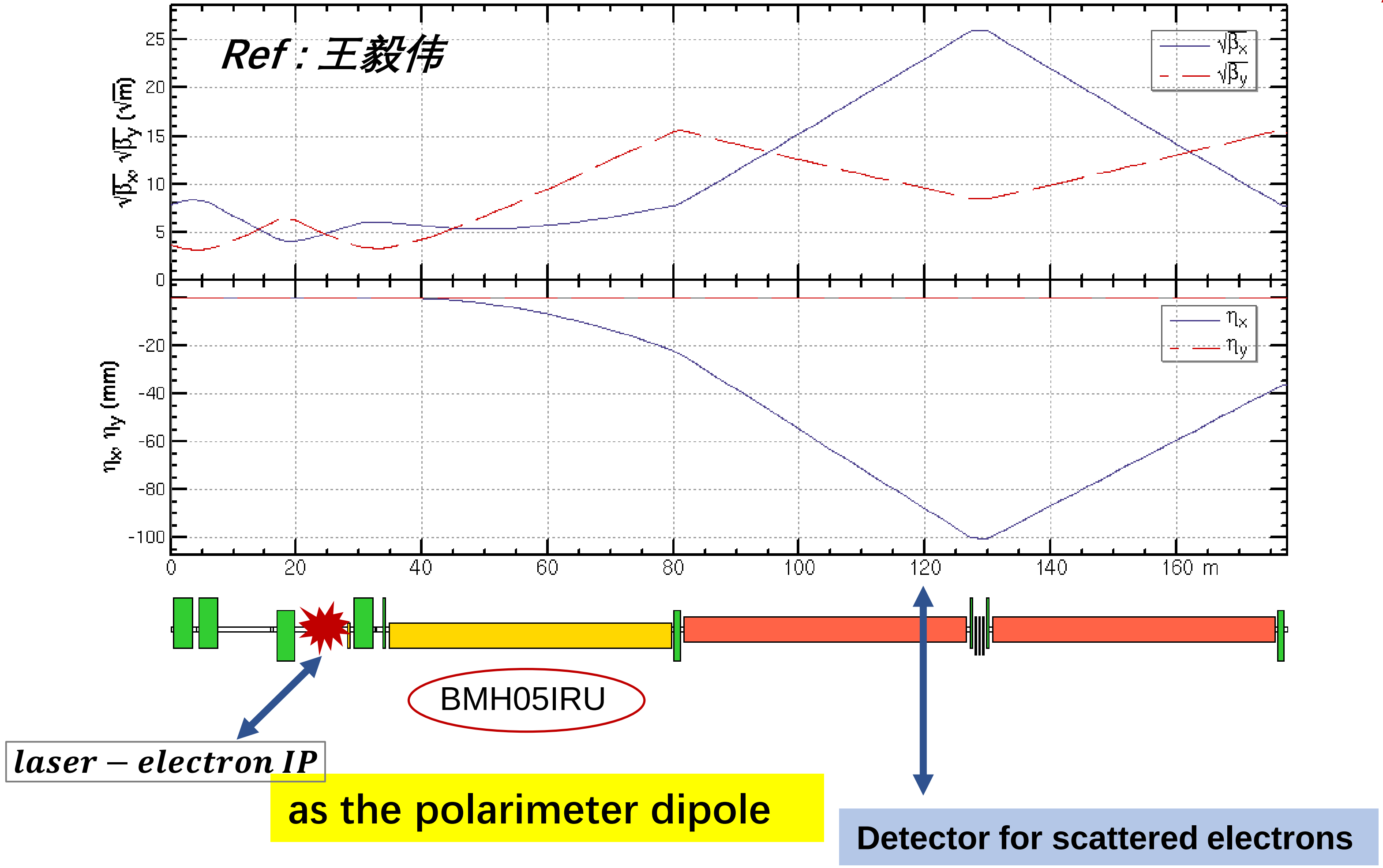


The lattics design and geometry of the interaction region for Z mode

Polarimeter position: A suitable location for the transverse polarimeter is the upstream before the e^+e^- IP region, about 1km before the IP.

CEPC lattice: Location of Polarimeter

➢ The polarimeter location:



Alternative location:

- The transverse polarimeter locate at the upstream before the e^+e^- IP region, about 1km before the IP.
- Dipole *BMH05IRU* is used as polarimeter bending magnet.
- After about 40m of free beam drift: allow separation of the Compton scattered photons and electrons from the beam.
- Laser-electron interaction point(IP) is located about 12m before the dipole *BMH05IRU.*

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

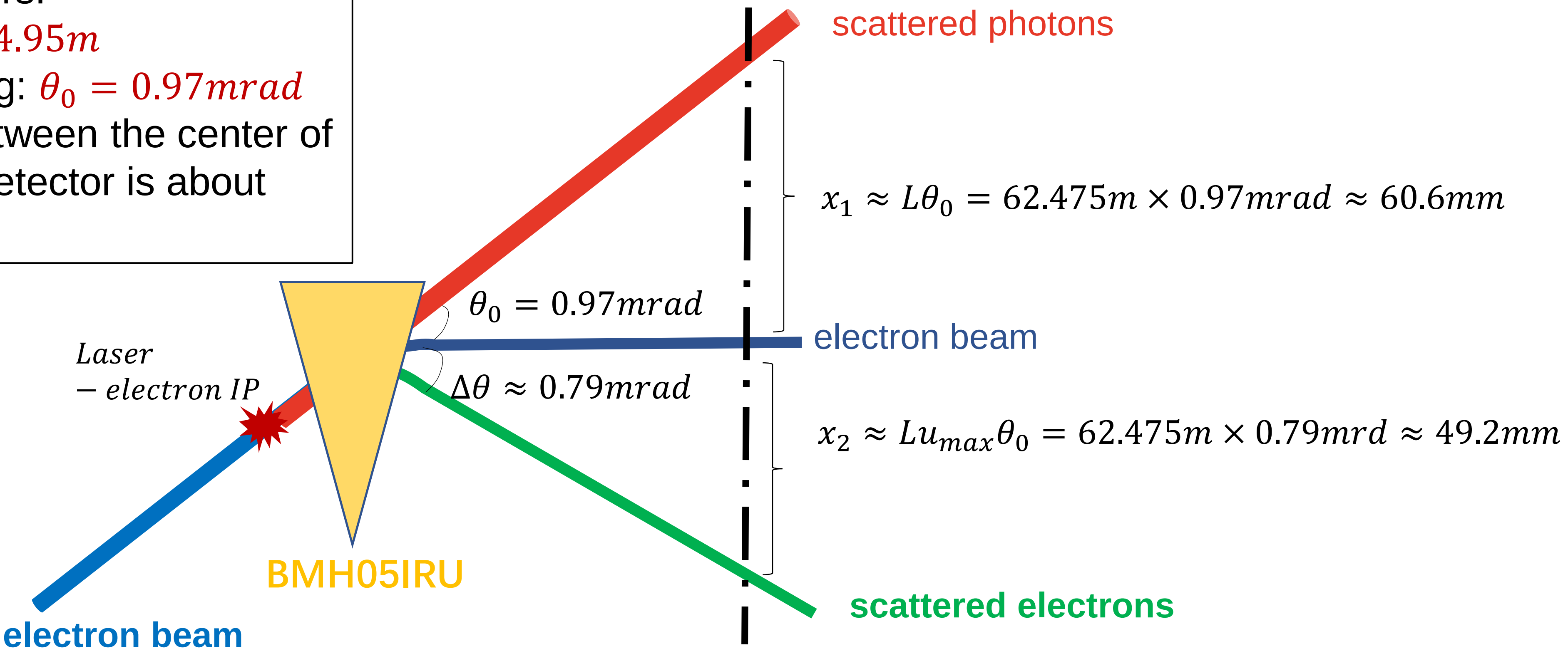
The transverse polarization can be measured based on **Compton back-scattering process.**

- By measuring the spatial position of the **scattered electrons.**

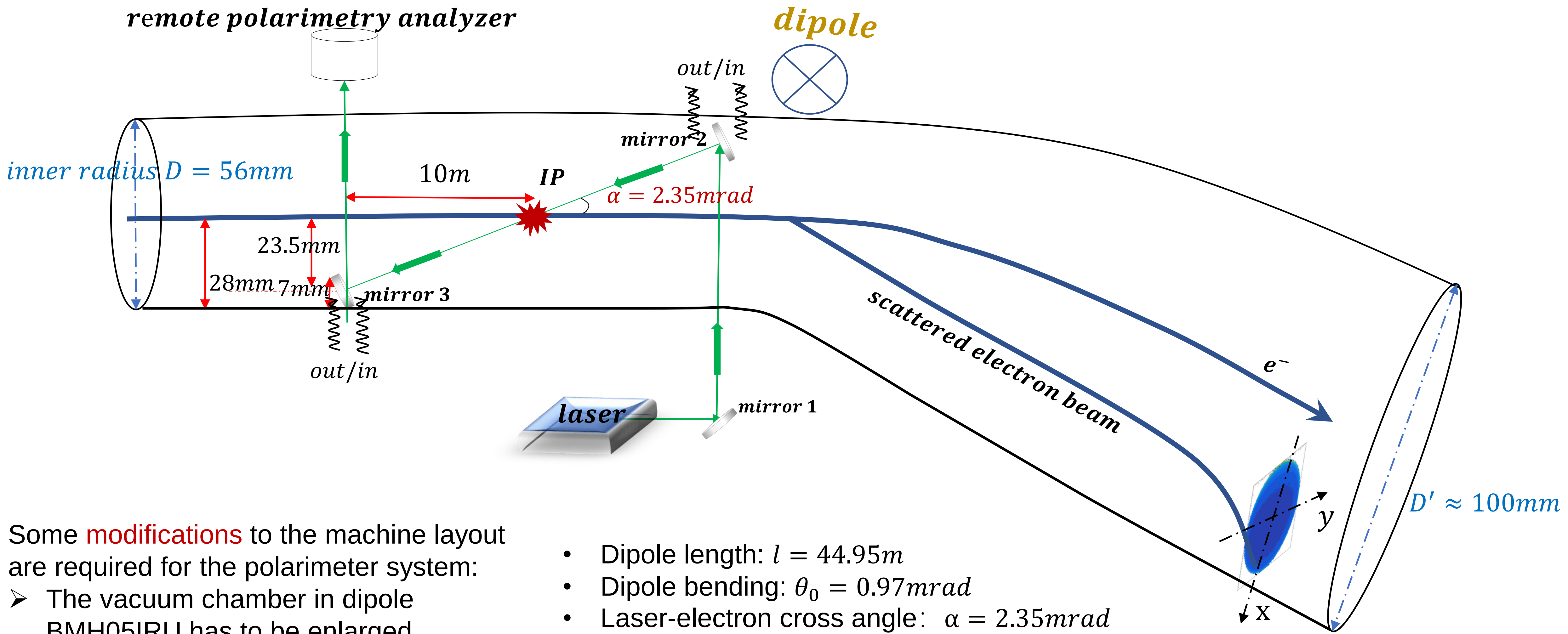
Dipole parameters:

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

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



Laser-electron interaction point region



Some modifications to the machine layout are required for the polarimeter system:

- ➢ The vacuum chamber in dipole BMH05IRU has to be enlarged.
- ➢ Fine focusing adjustment can be performed by the remotely movable mirror 2&3 and lens.

- 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: $L_2 = 62.475\text{m}$

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:

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

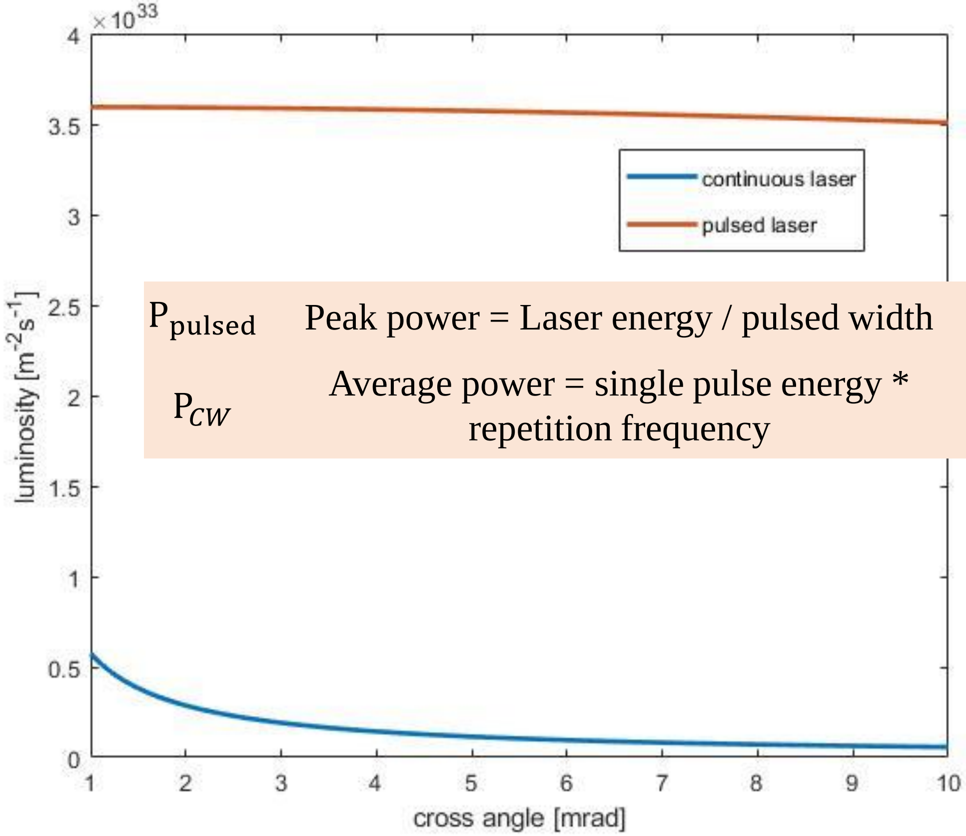
N_e — number of electrons per bunch, N_γ — number of photons per laser pulse
f — number of bunch crossing per second, α — cross angle of laser and electron (2.35mrad)
σ_e and σ_γ is the horizontal size of electron and laser

Luminosity comparisons

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

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

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



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:

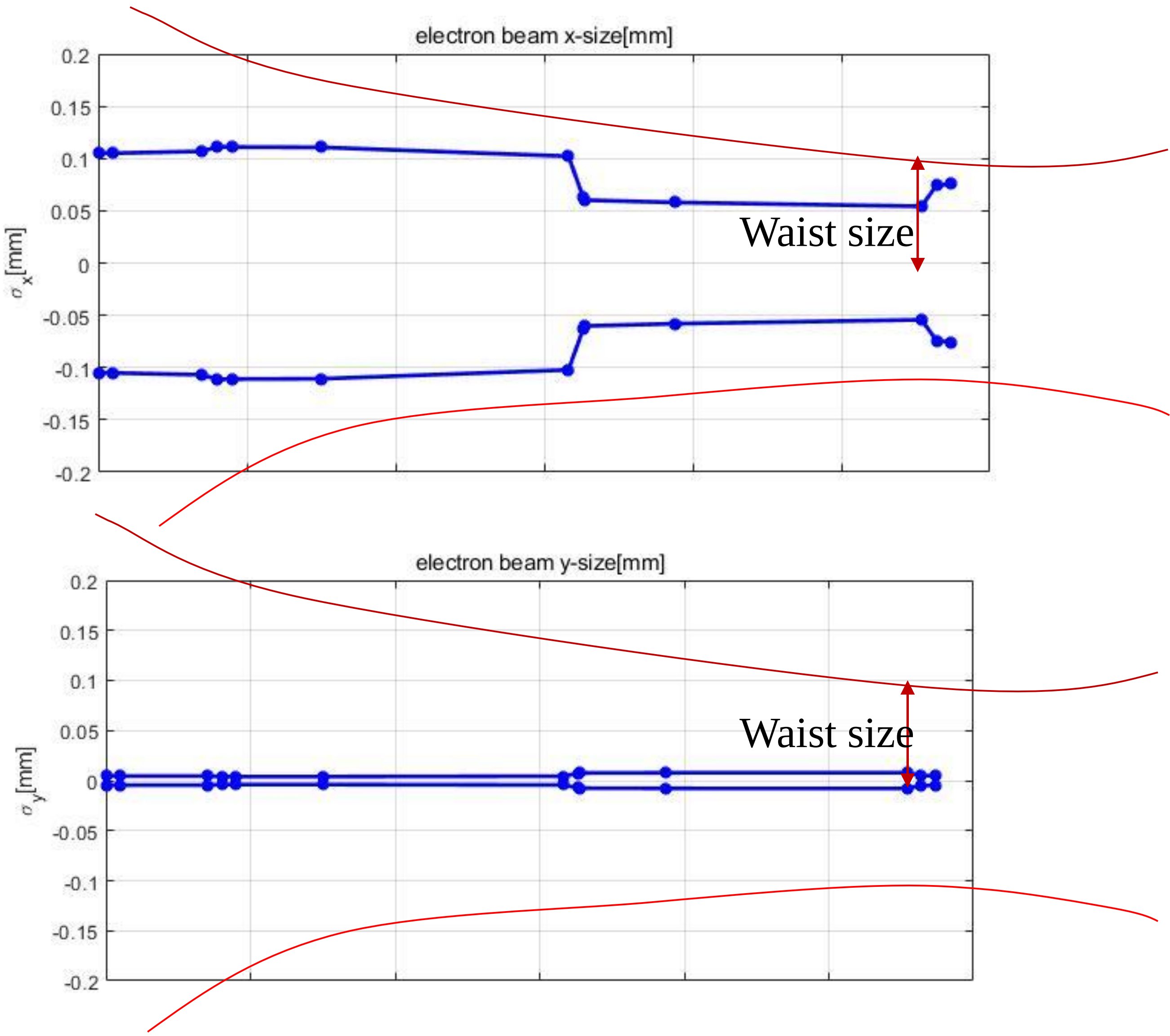
- Peak Power: For CW laser, the average power is relative low. A pulsed laser has high peak power that require more protection (for mirror system or coating process).
- For the beam disturbance: scattered events per collision for CW laser is less than for pulsed laser, which corresponding to the relative 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	
Average power	5 [W]
wavelength	1064[nm]
Waist size	$\sigma_0 = 100$ [μm]
Rayleigh length	$z_R = \frac{\pi\sigma_0^2}{\lambda} = 29.5$ [mm]



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

Compton polarimeter: Laser

- The luminosity for continuous wave(CW) laser

$$\mathcal{L}_{CW} = \frac{(1+cos\alpha)}{sin\alpha}\frac{I_e}{e}\frac{P_L\lambda}{hc^2}\frac{1}{\sqrt{\sigma_{e,y}^2+\sigma_{\gamma,y}^2}}\frac{1}{\sqrt{2\pi}} = 8.7\times10^{35}m^{-2}\cdot s^{-1}$$

I_e — bunch current， α — cross angle of laser and electron (2.35mrad)
σ_e and σ_γ is the horizontal size of electron and laser

- The cross section of Compton scattering

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

$$\kappa = \frac{4\omega_{laser}E_{beam}}{m_e^2}sin^2(\frac{\alpha}{2})$$

r_e — electron classical radius， ω_{laser}— 1.16eV(1064nm)
E_{beam} — 45.5GeV

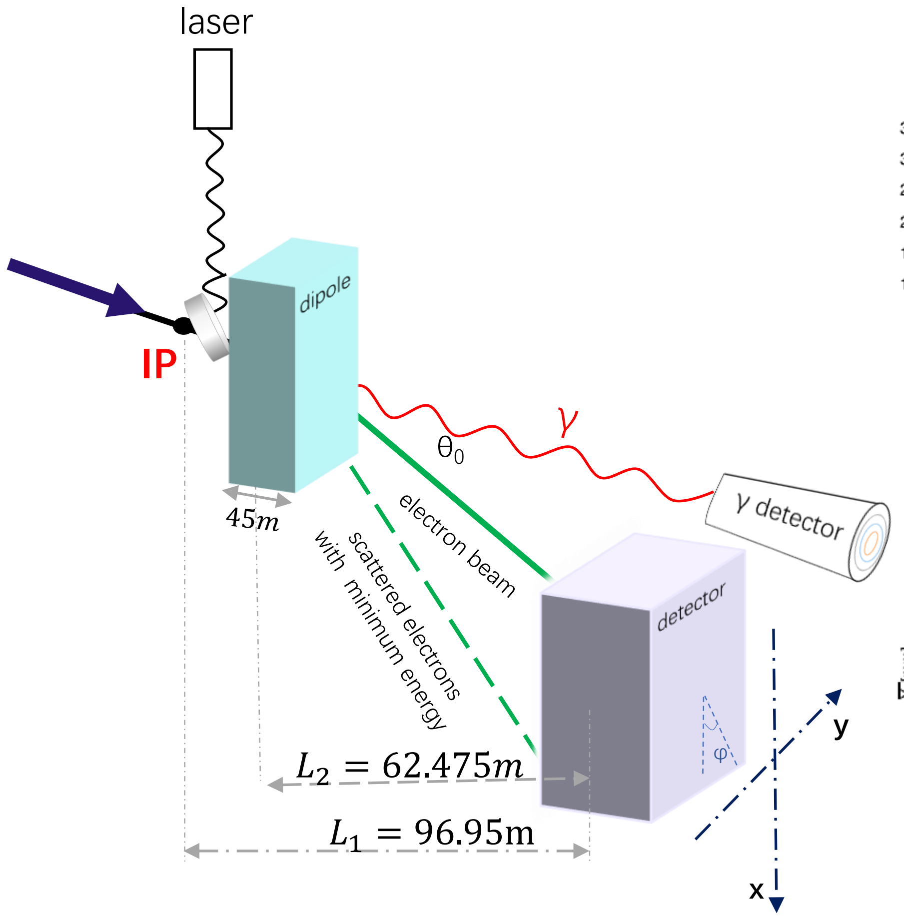
- The scattering events for collision

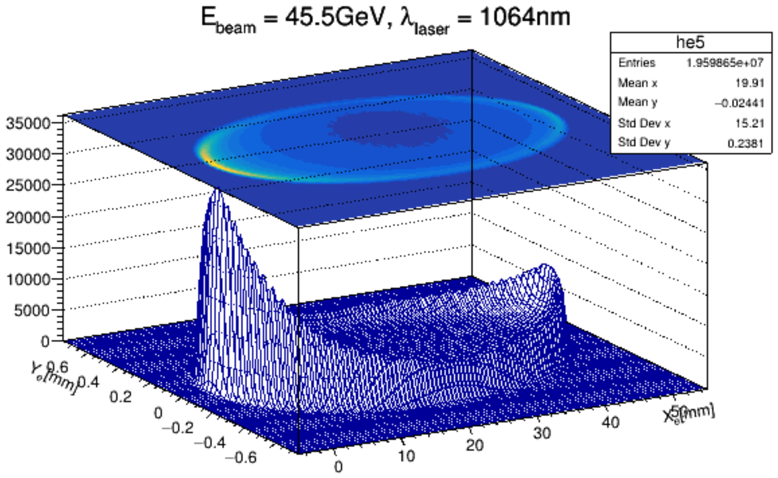
$$N = \mathcal{L}_{CW}\sigma = 8.7\times10^{35}m^{-2}\cdot s^{-1}\times 402mb \approx 3.497\times10^7$$

Simulation of scattered electrons

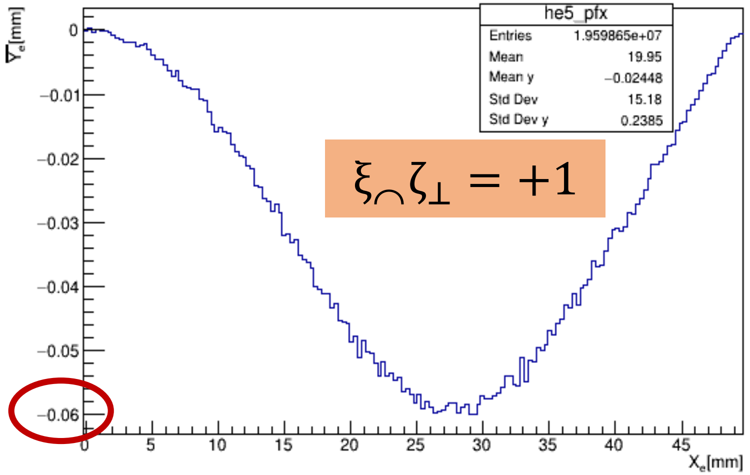
- The spatial distribution of scattered electron in the detector

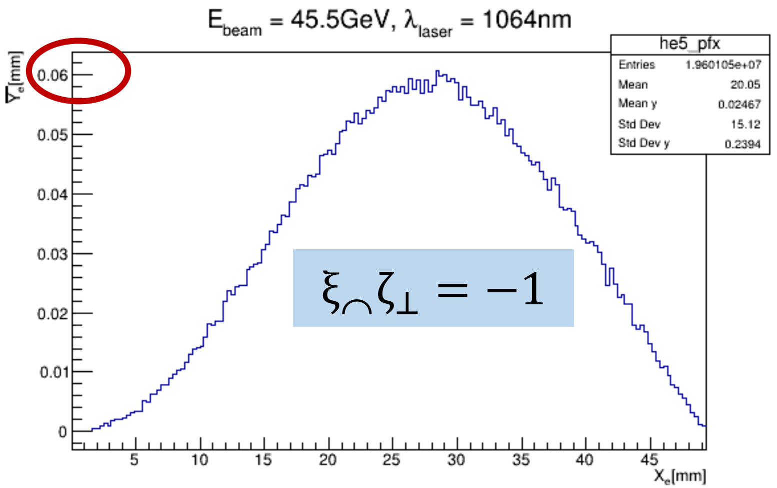
$\xi_{\frown}$ is laser circular polarization
$\zeta_{\perp}$ is electron beam transverse polarization

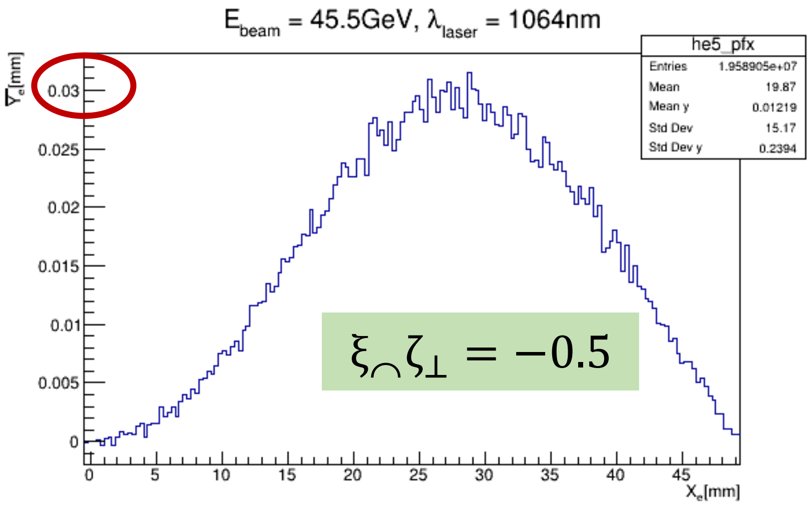




The 2D distribution of scattered electrons







The Profile X of scattered electrons with different polarization

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

10% transverse polarization

- **Detector design:**

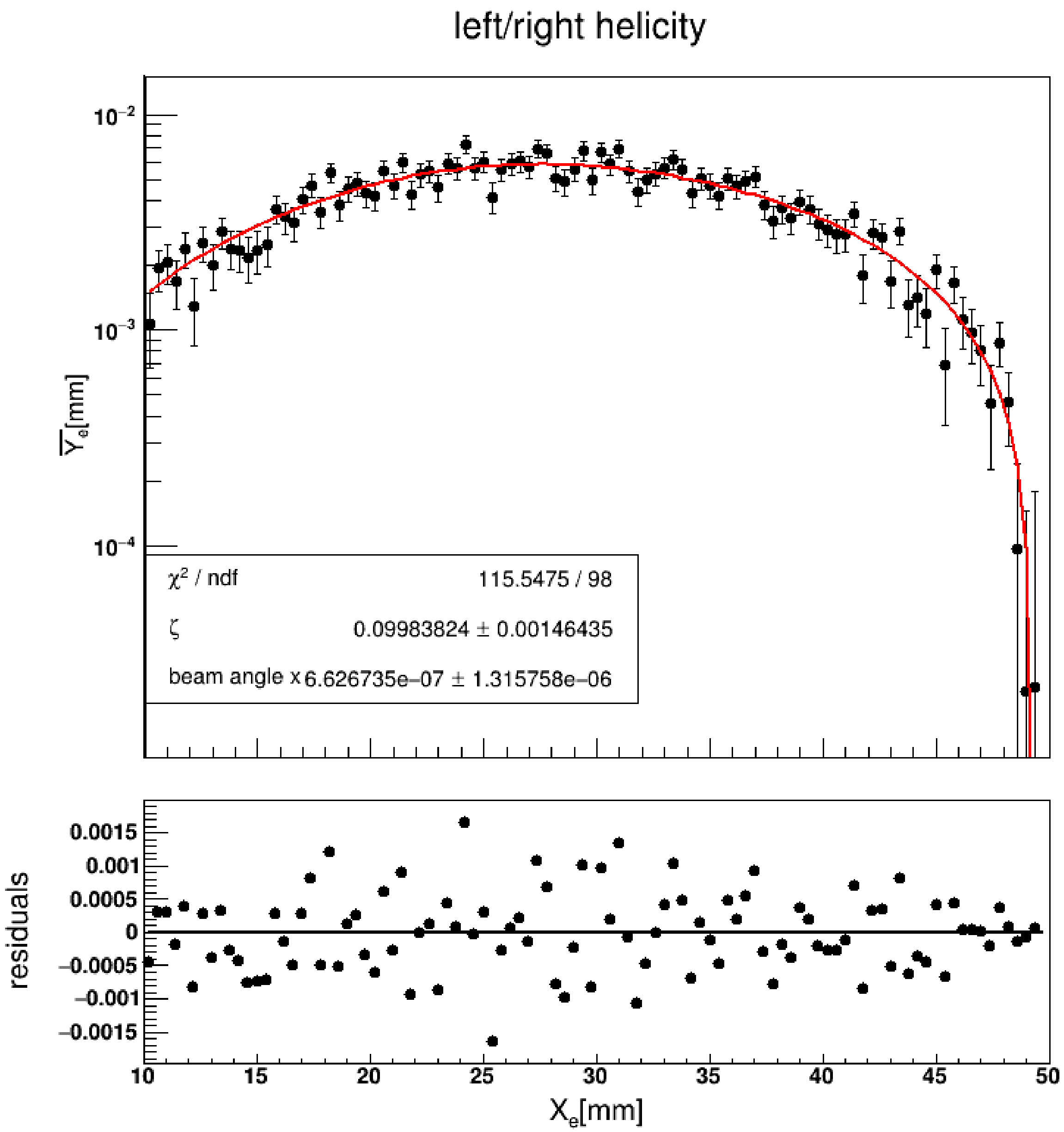
  X*Y = 40mm*1.5mm;
  Pixel size: 400μm*25μm
  (pixel Y is important !!!)

$$\frac{\overline{Y_e}|_{left\ helicity} - \overline{Y_e}|_{right\ helicity}}{2} = P_{\perp}\Pi(X_e)$$

$\Pi(X_e)$ — analyzing power as the fit funtion;
$P_{\perp}$— beam transverse polarization

- **The statistic error**

  In a collision(1s), the relative statistical error is about $\frac{\Delta P}{P} \approx \frac{0.001464}{0.099838} \approx 1.47\%$



Systematic uncertainties

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%**

Summary & outlook

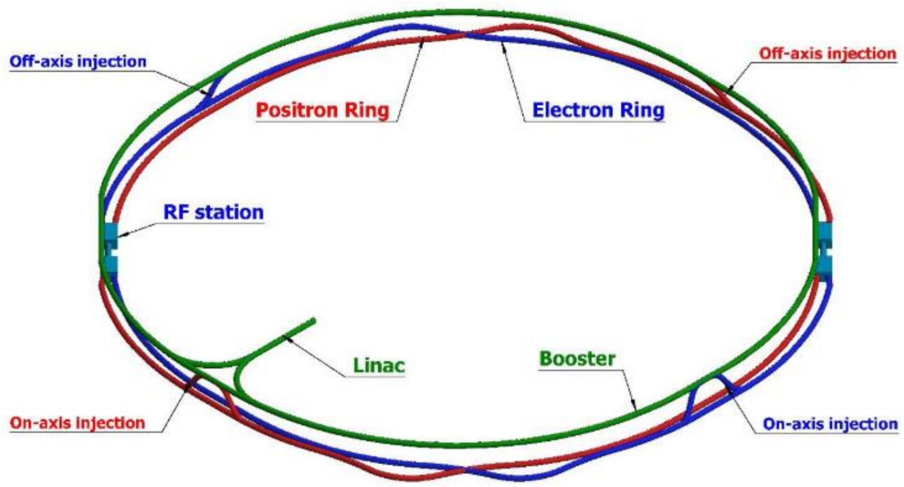
- The result is: (According to current location and design)
  - The transverse polarization measurement statistical error is $\Delta P_{\perp}/P_{\perp} \sim 1.47\%$ in 1s and systematic uncertainties is about $\Delta P_{\perp}/P_{\perp} \sim 1.13\%$

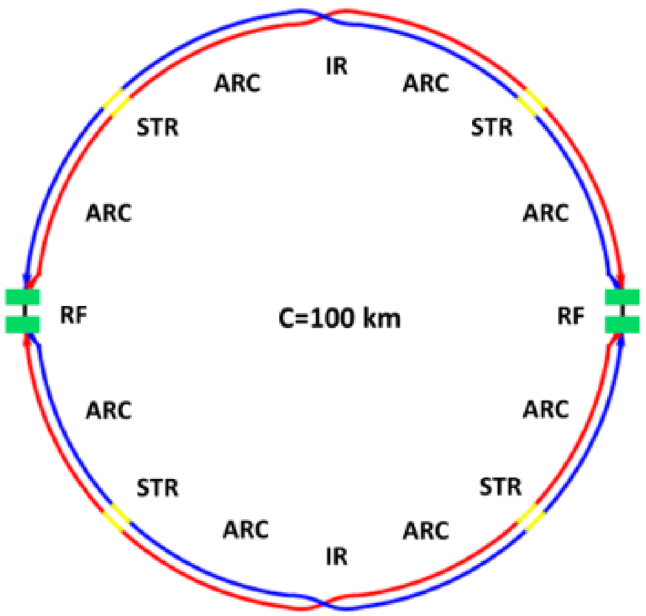
- Aiming to discuss the location & layout of polarimeter:

  Compton polarimeter requirement:
  - Electron parameter: small β-function smearing in X and Y.
  - Dipole and a clear distance to separate the scattered photons and electrons from beam.
  - Laser parameter: Enough luminosity for enough rate of scattered events.
  - Detect the spatial distribution of scattered electrons.

backup

CEPC layout





CEPC layout:

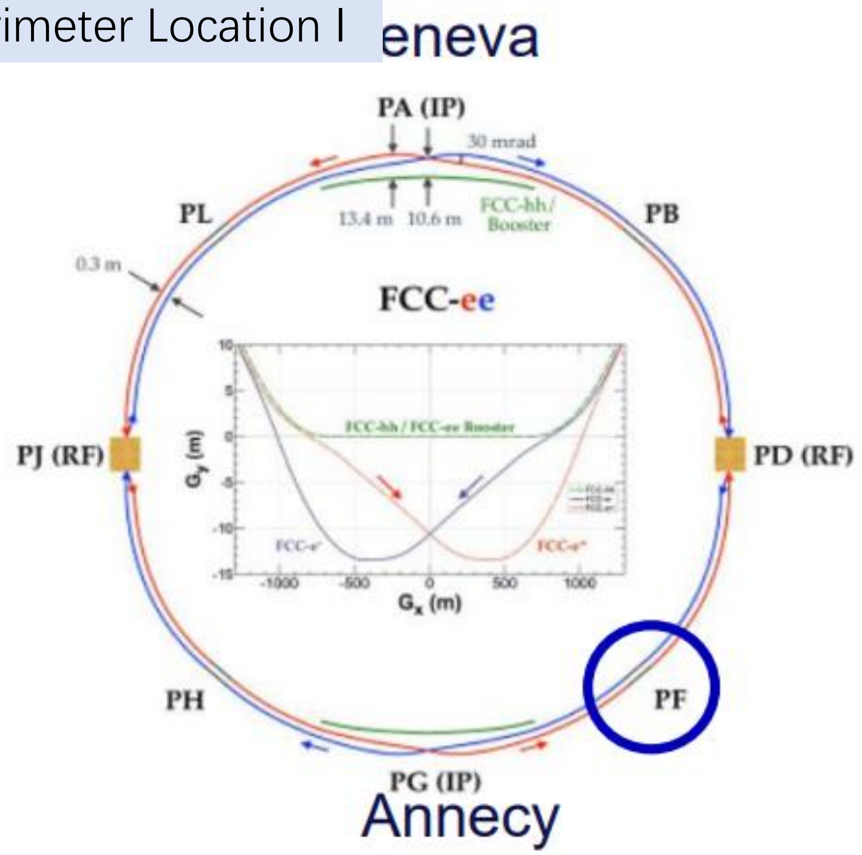
- 8 straight sections in the Collider: 2 interaction regions, 2 RF regions and 4 injection regions.
- Among them, two off-axis injection regions are for Higgs, W and Z modes
- The two on-axis injection regions are used only for Higgs mode

Table 1: The polarimeter in colliders

	Colliders	Type	Institution	
Circular	ACO	electron-positron	Orsay	Touschek lifetime
	VEPP-(2,2M,3,4)		BINP	Touschek lifetime (VEPP-2) Moller polarimeter (VEPP-3) Compton polarimeter (VEPP-4)
	SPEAR	electron-positron Storage ring	SLAC	Compton polarimeter (first)
	DORIS		DESY	Compton polarimeter
	PETRA			Compton polarimeter
	CESR		The Cornell University	Compton polarimeter
	KEKB	electron−positron	KEK	Compton polarimeter
	TRISTAN			Compton polarimeter
	LEP		CERN	Compton polarimeter
	FCC-ee			Compton polarimeter
	HERA	electron(positron)-proton	DESY	Compton polarimeter
	EIC	Electron-ion collider	BNL	Compton polarimeter
Linear	SLC	electron−positron	SLAC	Compton polarimeter
	ILC	electron−positron	Japan	Compton polarimeter

FCC-ee

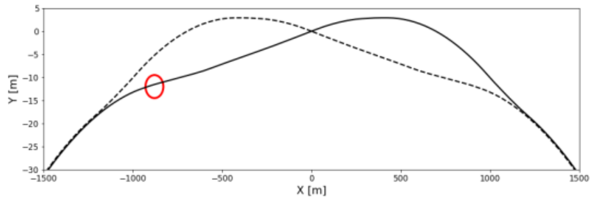
Polarimeter Location I

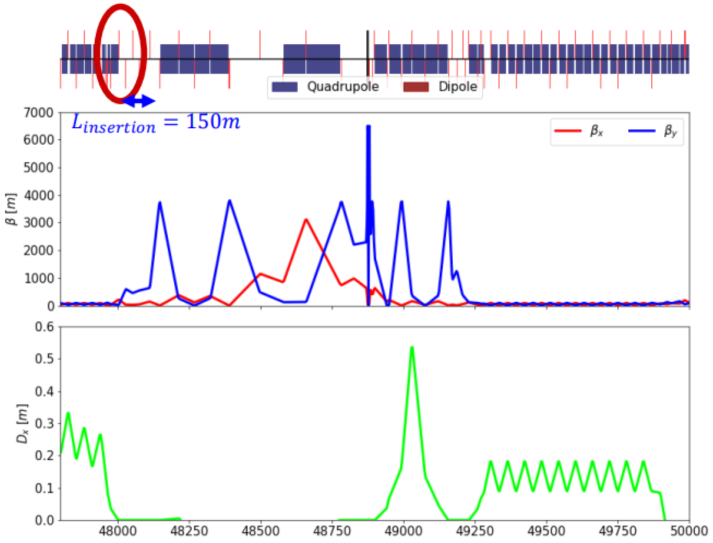


A suitable location for the laser-beam intersection point is upstream of the last dispersion suppressor magnet on the beam located inside the ring in the insertions at Points PH and PF.

Polarimeter Location II

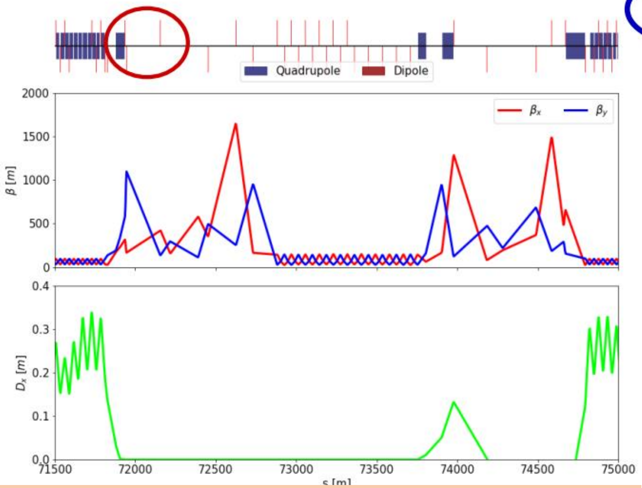
- Alternative locations:
  - Experimental straight section
    - Larger beam separation gives more space for detectors (close to FCC-hh Exp cavern)
    - Geometry will need modifications and constrained by sub 100 keV critical energy of downstream dipoles

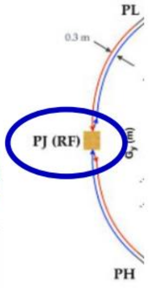




Polarimeter Location III

- Alternative locations:
  - Experimental straight section
  - RF straight
    - Acting on outside beam
    - "Noisy" environment





Ref:[1]https://indico.cern.ch/event/1080577/contributions/4545364/attachments/2324366/3958735/MH_FCCee_PolLocation.pdf

DOI: 10.1088/1748-0221/15/08/C08024

VEPP-4M

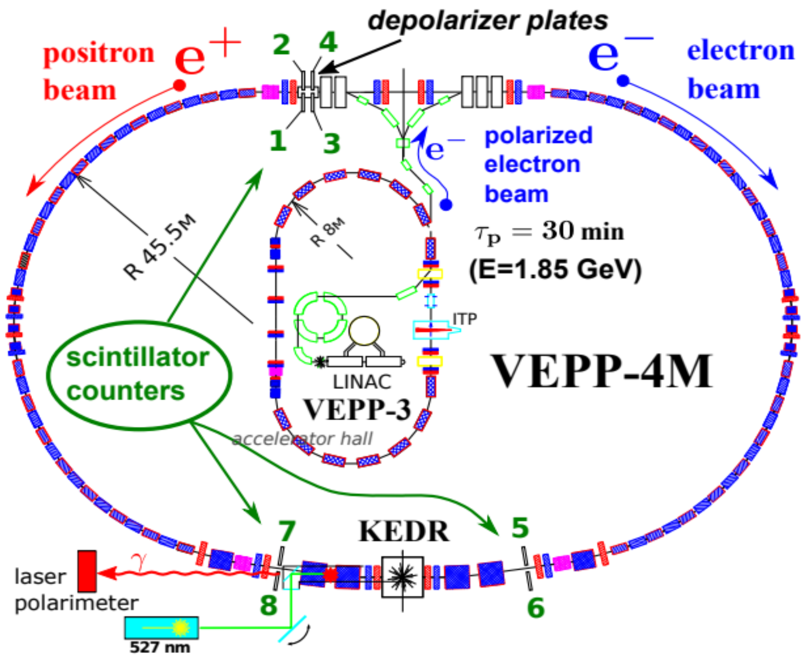


Figure 2. Location of Laser polarimeter at VEPP-4M collider.

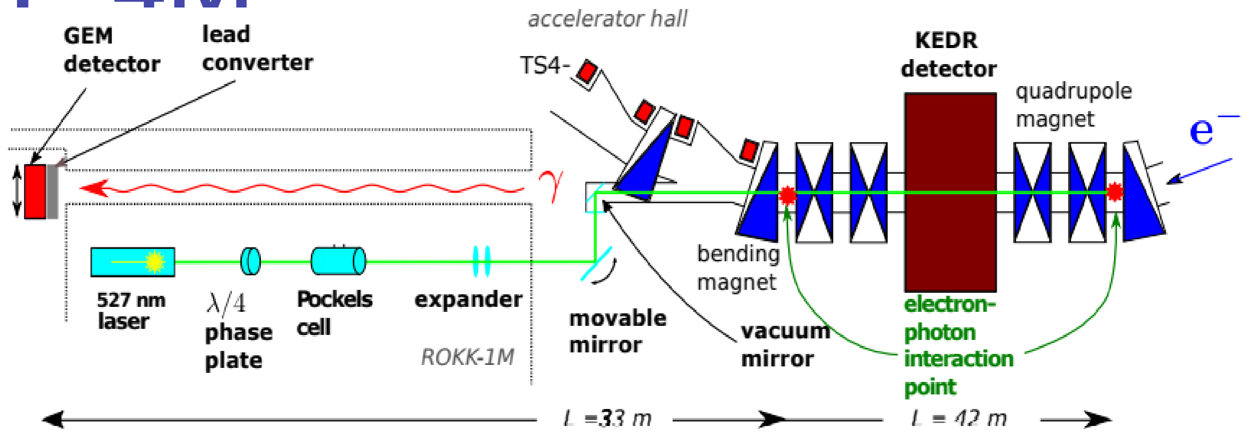


Figure 3. Scheme of the Laser polarimeter at VEPP-4M.

laser	Solid state Nd:YLF pulse laser
wavelength	527nm (2.35eV)
Pulse duration	5ns
Time jitter	2ns
Maximum pulse repetition	4kHz
Average power	2W
IP laser beam size	1mm
IP Rayleigh length	1m
Number of Scattered photons	10kHz/mA
IP minimal angular momentum spread	20 × E[GeV]/1.5μrad

- Laser polarimeter is located near experimental hall of VEPP-4M collider in the ROKK-1M room.
- The optical system of the laser polarimeter shares some equipment (laser device, focusing system, Compton backscattering rate control) with the KEDR Tagging System calibration

SPEAR

https://doi.org/10.1016/0029-554X(79)90268-4

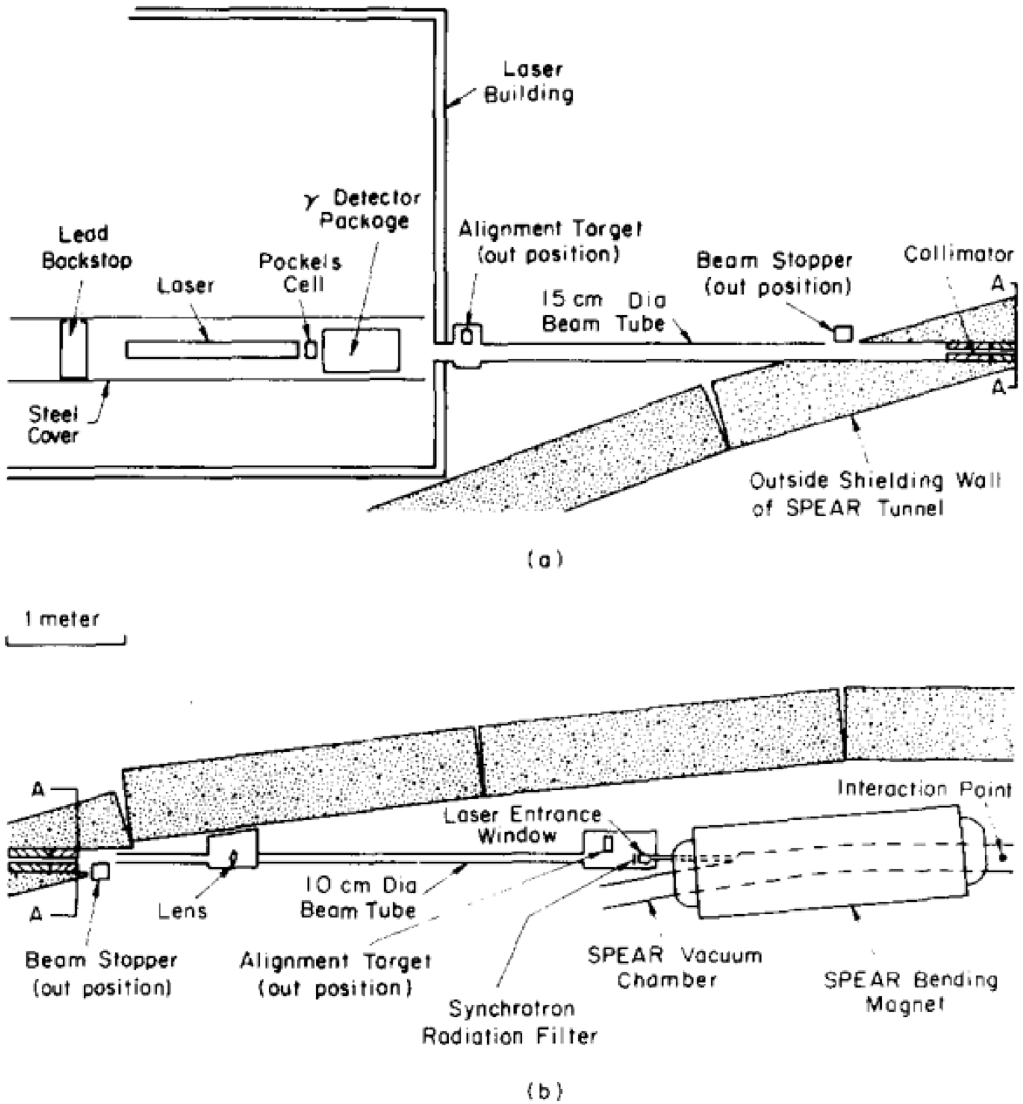


Fig. 5. Plan view of the experimental layout (a) outside and (b) inside the SPEAR shielding tunnel.

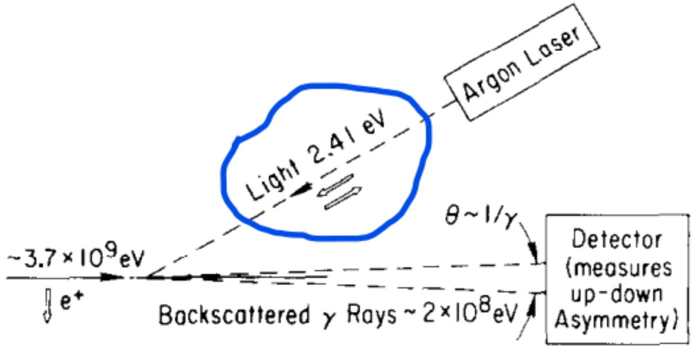


Fig. 1. Schematic layout of apparatus. Open arrows indicate polarization states.

laser	Cavity-dumped argon-ion laser
wavelength	514.5nm (2.41eV)
Each Optical pulse width	12~15ns
peak power	80W

LEP

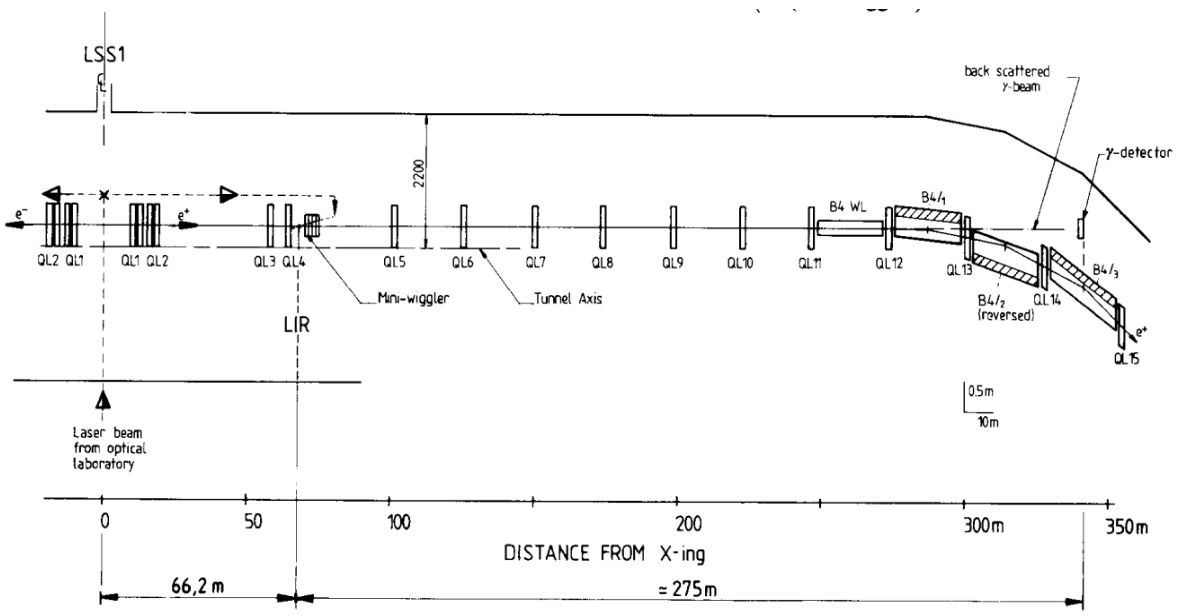


Fig. 4. General layout of the LEP polarimeter for positrons in LSS1.

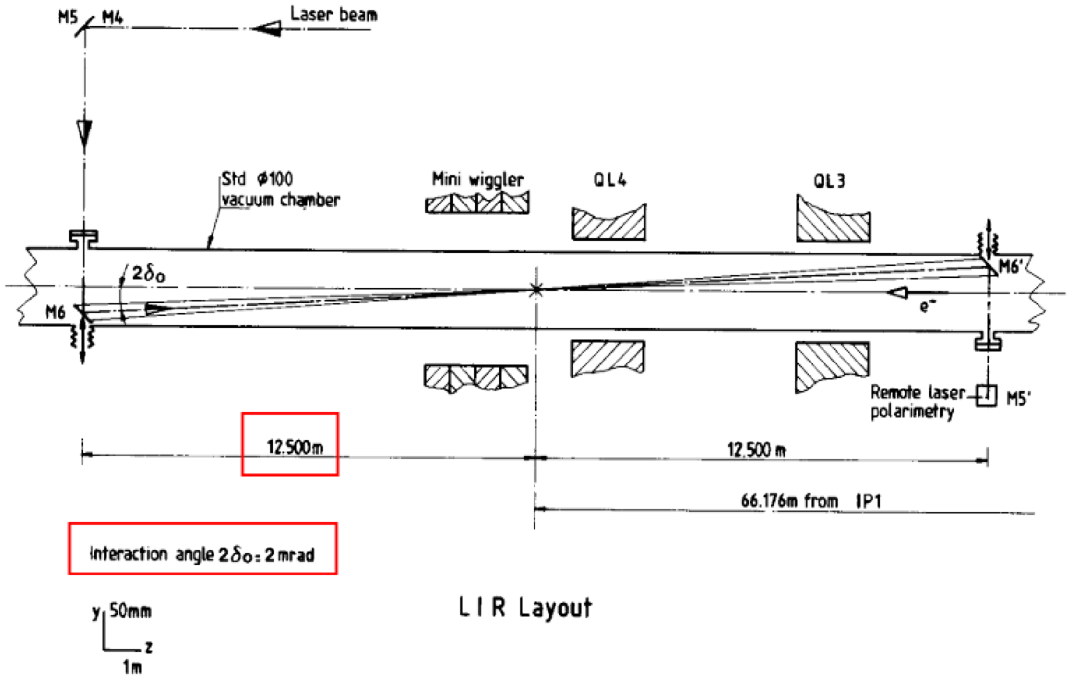


Fig. 6. Layout of the laser–electron interaction region (LIR).

- 系统的设置要考虑来自主磁铁（main dipoles）产生的同步辐射对探测器的影响。
- 激光器安装在Optical Laboratory，产生光子束；
- Electron-laser interaction region(LIR)位于QL4和QL5之间。距离QL4 1米。
- 光子探测器距离LIR 275米，距离IP1点341米。
- LIR最后的一块镜子将选用金属材质的镜子用于偏转laser去与电子束对撞。

Table 3
Laser beam optics at LIR

Diffraction limited beam size at focus [mm]	0.4
Nominal beam size at focus [mm]	2.4
Full angle divergence at focus (max) [mrad]	≤ 2.7
Nominal beam size at the optical systems (max) [mm]	≤ 35
Final optical system aperture [mm]	50
Final optical system focal length [m]	10.3
Mirror M_6 size [mm^2]	36 × 50
Mirror to electron beam clearance [mm]	≥ 10
Interaction angle [mrad]	≥ 2

Table 4
Laser technical specifications. Laser type: Nd:YAG Quantel COMPAC – YG661S longitudinal monomode

Wavelength [nm]	523	
Photon energy [eV]	2.33	
Repetition rate [Hz]	10	30
Peak power [MW]	50	30
Pulse length (FWHM) [ns]	5–6	6–7
Pulse energy [mJ/pulse]	300	190
Peak intensity [10^{18} ph/pulse]	≈ 0.8	≈ 0.5
CW power [W]	3	5.7
Time jitter (rms) [ns]	0.25	0.3
Output emittance ($\sigma\sigma'$) [μm]	0.3	0.4
Output cavity beam diameter (4σ) [mm]	6	6
Full angle divergence ($4\sigma'$) [mrad]	0.8	1

https://www.sciencedirect.com/science/article/pii/0168900289903677

LEP

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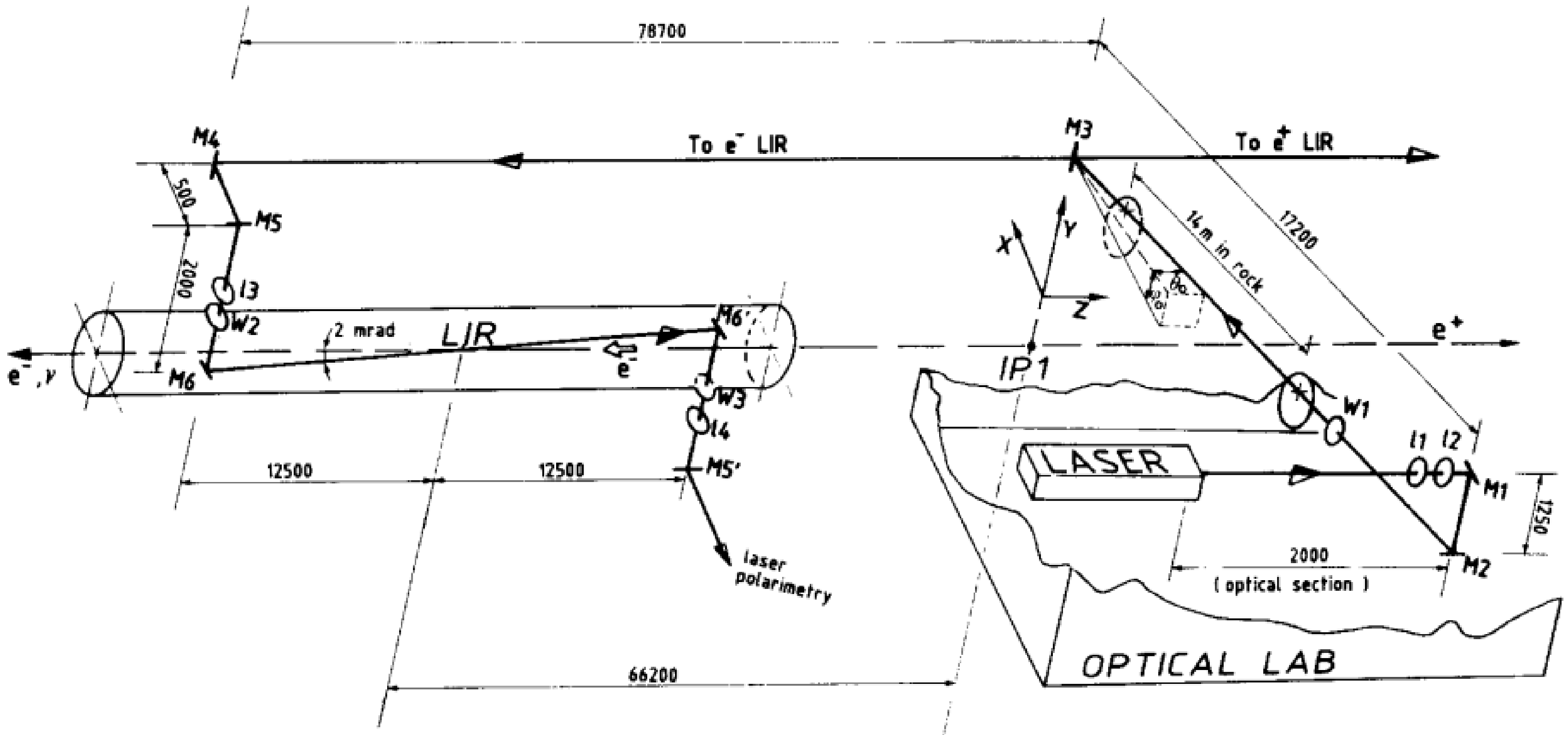

Fig. 11. Geometry of the laser beam transport line. Deflections at mirrors:

M_1: 90° M_3: 103°42′ (e^-), 76° 18′ (e^+) M_5: 90°

M_2: 103°26′ M_4: 90° M_6: 90° − 2 mrad = 89°53′08″.

$\vartheta_0 = 13°42'$ $\phi_0 = 13°26'$.

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