Compton Polarimeter for CEPC

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On behalf of the BEMS team

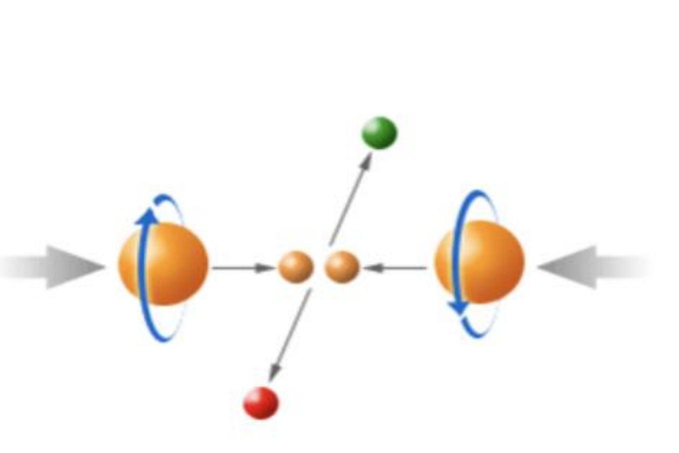
Outline

- Motivation of CEPC Z-pole polarized beam program
- Compton Polarimeter for CEPC
- The measurements of beam transverse polarization(Z pole)
- The toy MC simulations
- The fit results of transverse polarization
- Discussion & Summary

Motivation of CEPC Z-pole polarized beam program

- Transversely polarized beams in the ARC
  - Beam energy calibration via the resonant depolarization technique(Accuracy 10^{-6})
  - Essential for precision measurements of Z and W properties
  - At least 5% ~ 10% transverse polarization, for both e+ and e- beams

- Longitudinally polarized beams at IPs
  - Beneficial to colliding beam physics programs at Z, W and Higgs(weak interactions & spin structure of particle)
  - ~50% or more longitudinal polarization is desired, for one beam, or both beams

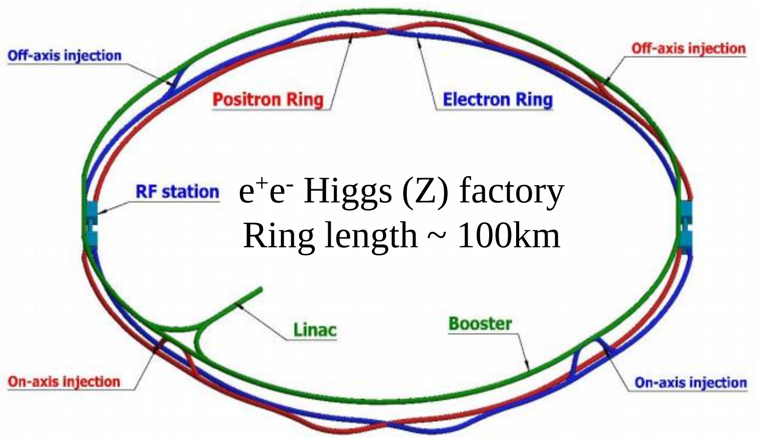


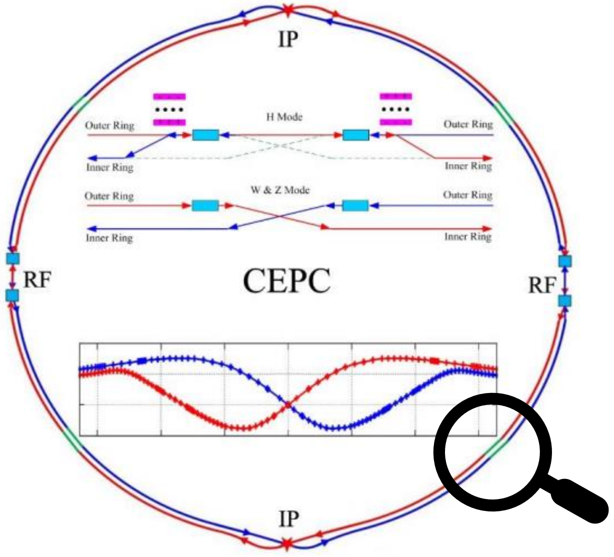
Ref: [1]L. Arnaudon, et al., Z. Phys. C 66, 45-62 (1995).
[2]Zhe Duan, CEPC Z-pole Polarization Study Status, CEPC Day Feb 25, 2021. https://indico.ihep.ac.cn/event/13810/

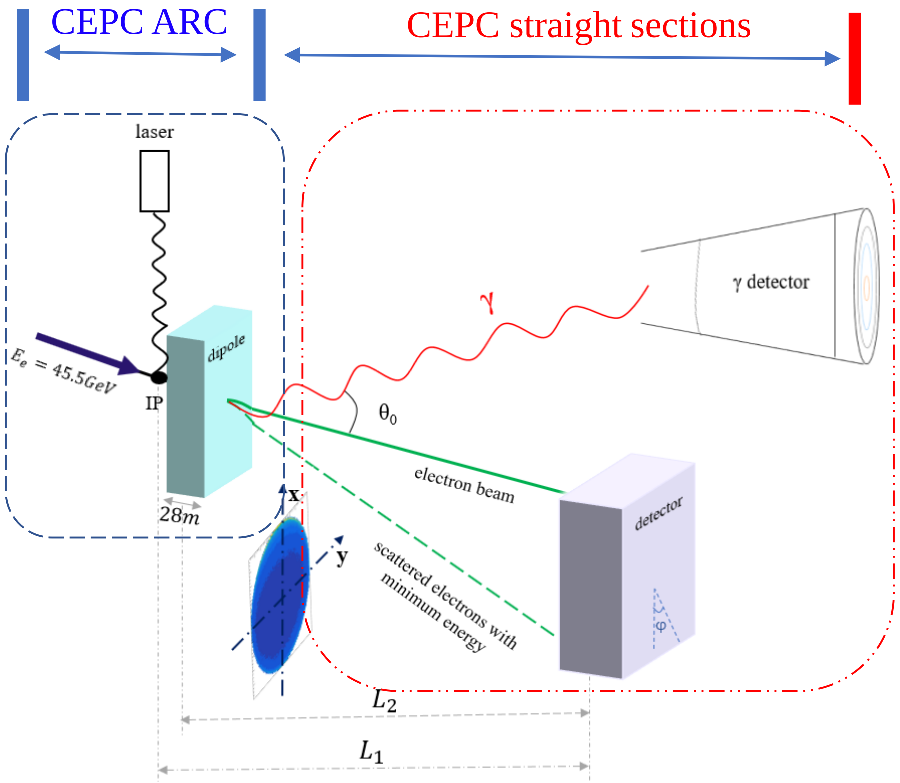
Compton Polarimeter at CEPC(Z pole)

- **Discuss the system layout(for transverse polarization)**

△ Compton Polarimeter







- **Prospects for the Compton polarimeter system:**
- Arrange our device in straight sections on the ring.(ensuring not affect the normal operation of beam on the ring)
- The last dipole in the ARC can be used as our bending magnet for our Compton polarimeter.
- **Note that:** the layout above is only aimed at measuring transverse polarization, the longitudinal polarimeter must located between two spin rotators(will discuss in the future)

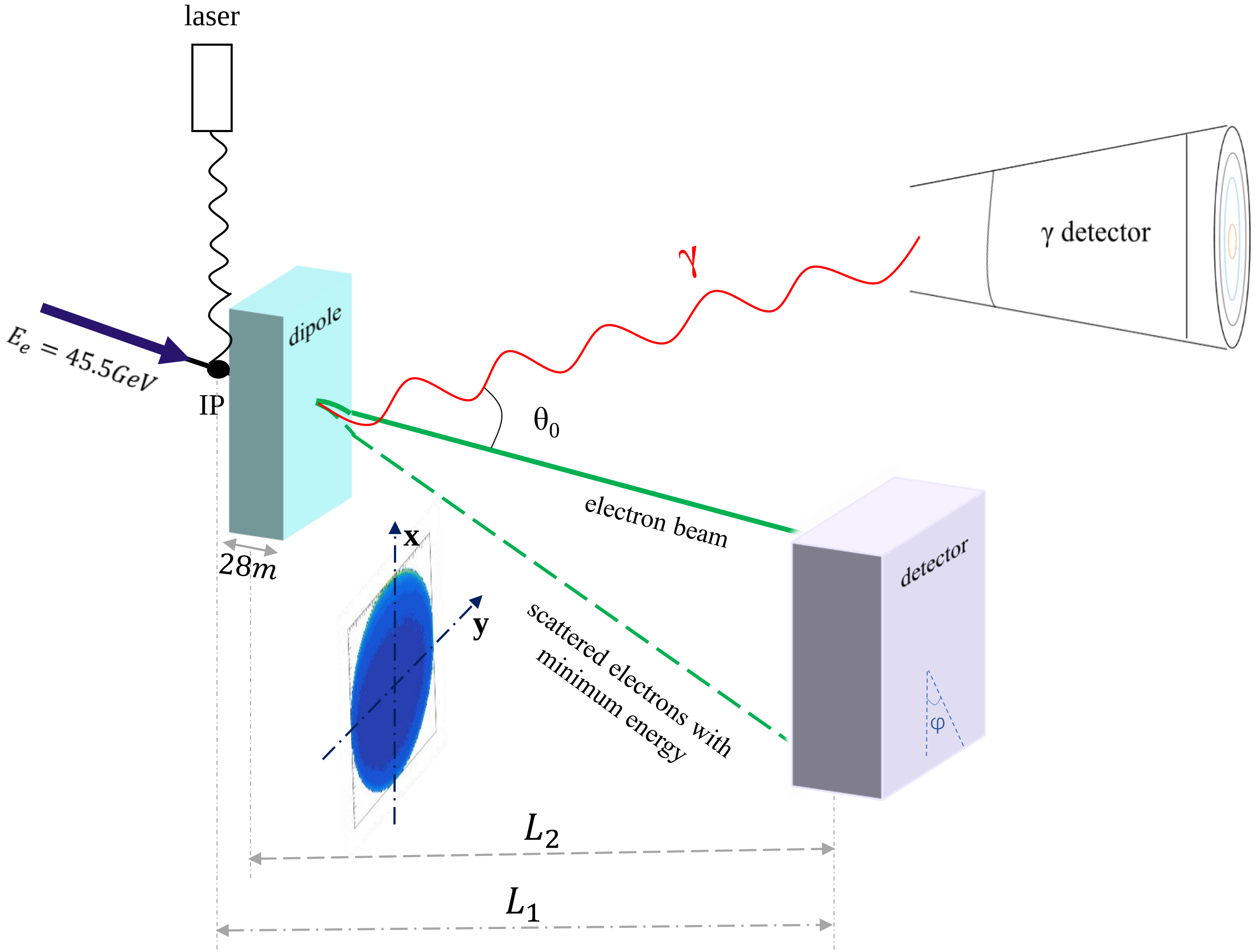
Dipole parameter(CDR): $B = 0.01867T \quad l = 28m$

Draft distance(Our Preliminary design):

- $L_1 = 60m$; $L_2 = 40m$
- Meaning that after dipole the scattered particle will drift $40m - 28/2 = 16m$

Compton Polarimeter at CEPC(Z pole)

Parameters	
E	$45.5\ [GeV]$
Laser	$1.24\ [eV]$
Dipole	$B = 0.01867[T]$
	$l = 28\ [m]$
	$\theta_0 = 3.4467[mrad]$
Drift distance	$L_1 = 60\ [m]$
	$L_2 = 40\ [m]$
Beam angle (at IP of laser and electron beam)	β_x =121m
	β_y = 15m
	ϵ_x =0.18nm
	ϵ_y =0.004nm
	σ'_x = 1.2197 [μrad]
	σ'_y = 0.5164 [μrad]



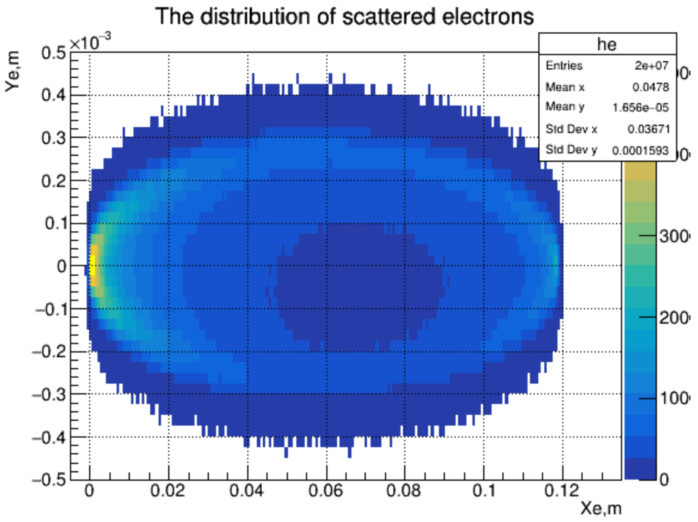
The distribution of scattered electrons

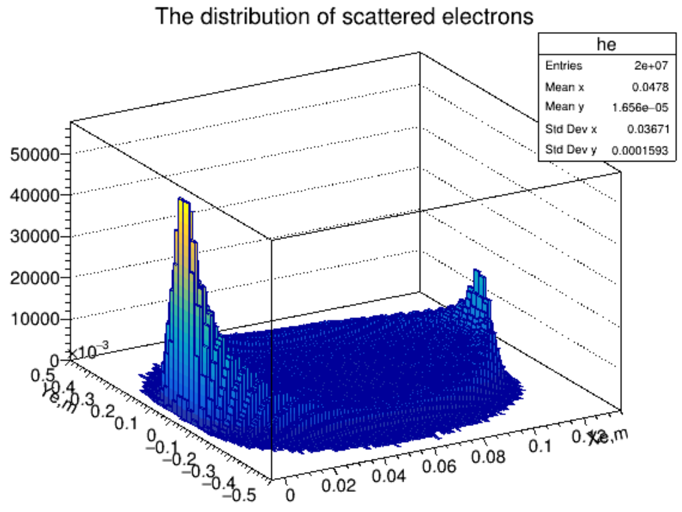
- **A toy MC**

$$X_e = \sigma_x' L_1 + \frac{L_1}{\gamma}\sqrt{u(\kappa - u)}\cos\varphi + u\theta_0 L_2$$

$$Y_e = \sigma_y' L_1 + \frac{L_1}{\gamma}\sqrt{u(\kappa - u)}sin\varphi$$

Where σ_x'/ σ_y' are horizontal and vertical electron angle ;
L_1:Distance between IP and detector;
L_2:Distance between Dipole and detector;
$u = \frac{\omega}{\varepsilon}$(the ratio of energy of scattered photons and scattered electrons);
$u \in [0, \kappa]$





The detector resolution has been considered in MC simulation

$$X \sim smear(X_e, 202.07\mu m)$$

$$Y \sim smear(Y_e, 7.2168\mu m)$$

The active dimension of detector ：$140mm \times 1mm$
The pixel size : $700\mu m \times 25\mu m$
The pixel number : 200×40
The resolution of the detector($\sqrt{12}$) : $202.07\mu m \times 7.2168\mu m$

Compton Scattering cross section

- **The fit function----Analyzing power $\Pi(Xe)$**

- The distribution of scattered electrons depends on electron polarization(ζ) and laser polarization(ξ)

$$d\sigma_0 = \frac{r_e^2}{(1+u)^3\sqrt{1-x^2-y^2}}\left(1+(1+u)^2-4\frac{u}{\kappa}(1+u)\right) dxdy$$

$$d\sigma_\parallel = \frac{\xi_\circlearrowright \zeta_\circlearrowright r_e^2}{\kappa(1+u)^3\sqrt{1-x^2-y^2}}u(u+2)\left(1-2\frac{u}{\kappa}\right) dxdy$$

$$d\sigma_\perp = -\frac{\xi_\circlearrowright \zeta_\perp r_e^2}{(1+u)^3\sqrt{1-x^2-y^2}}uy \quad dxdy$$

Ref: Nickolai Muchnoi, "FCC-ee polarimeter," arXiv e-prints , arXiv:1803.09595 (2018).

$$x = \frac{(X_e - \sigma_x' L_1) - \frac{\kappa}{2}\theta_0 L_2}{\frac{\kappa}{2}\sqrt{(\frac{L_1}{\gamma})^2 + (\theta_0 L_2)^2}} \qquad y = \frac{Y_e - \sigma_y' L_1}{\frac{L_1}{\gamma}\frac{\kappa}{2}} \qquad <u> = \frac{\theta_0 L_2}{\sqrt{\left(\frac{L_1}{\gamma}\right)^2 + (\theta_0 L_2)^2}}\frac{\boldsymbol{\kappa}}{\mathbf{2}}\boldsymbol{x} + \frac{\boldsymbol{\kappa}}{\mathbf{2}}$$

Note that: In our simulation, we consider laser beam has no linear polarization and electron beam has no longitudinal polarization

- The average y is given by:

$$<y> = \frac{\int y \frac{d\sigma}{dxdy} dy}{\int \frac{d\sigma}{dxdy} dy}$$

- Use it to obtain the transverse polarization:

$$\Delta <y>|_{Xe} = \frac{<y>|_{left} - <y>|_{right}}{2} = \zeta_\perp \, \Pi(Xe)$$

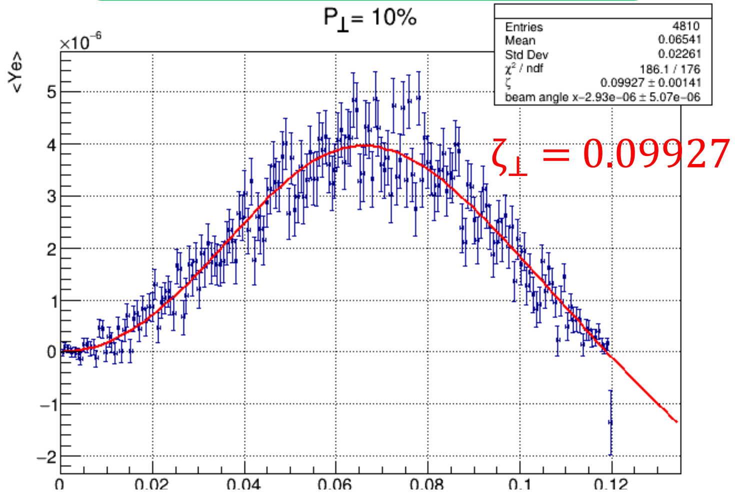
- Analyzing power Π:

the Analyzing Power of the polarimeter is its value for a 100% polarization.

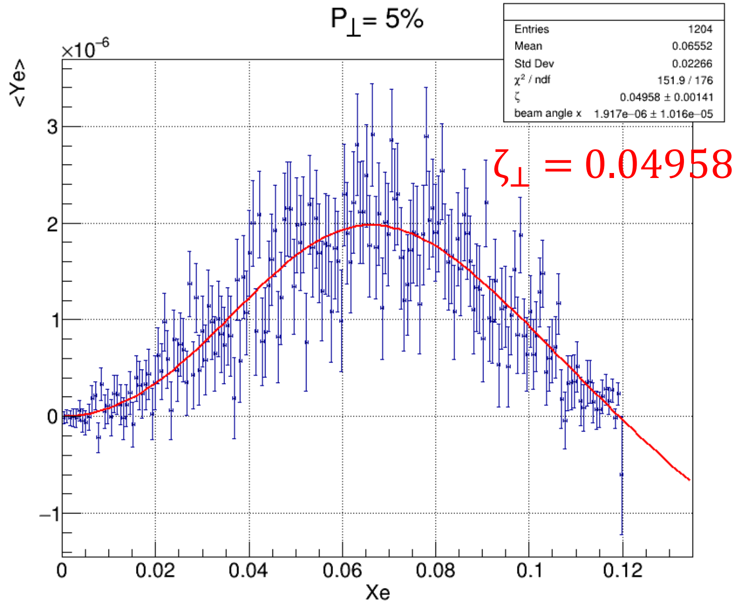
Polarization Measurement via Compton Polarimeter

- **The method**

The fit result of
Polarization = 10% and 5%



$\zeta_{\perp} = 0.09927 \pm 0.00141$



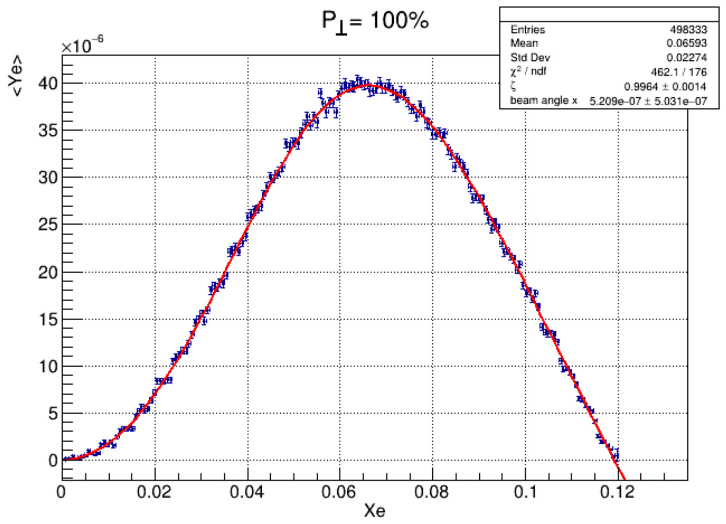
$\zeta_{\perp} = 0.04958 \pm 0.00141$

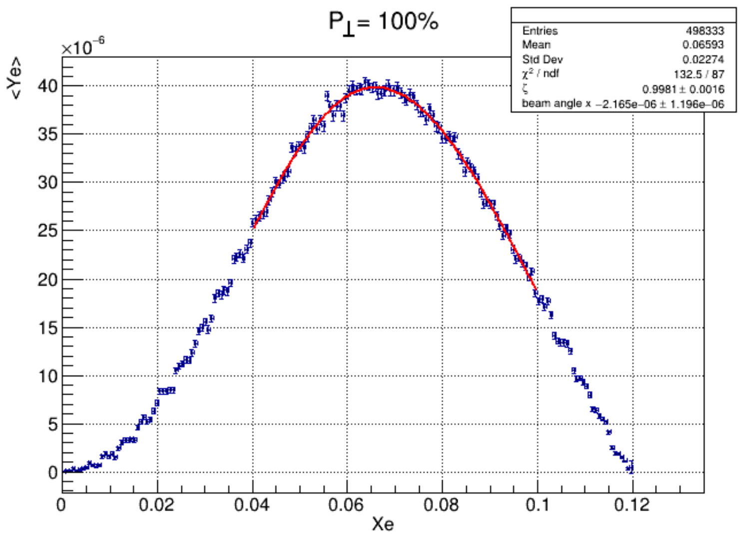
- 1. Obtain the 2D distribution scattered electrons
- 2. Projection
  - Projection onto the X-axis and add up the Y coordinates of each X bin
- 3. we fit the asymmetry:
  - $\Delta < y > |_{Xe} = \zeta_{\perp} \, \Pi(Xe)$
  - Where the transverse polarization $\zeta_{\perp}$ is fit parameter

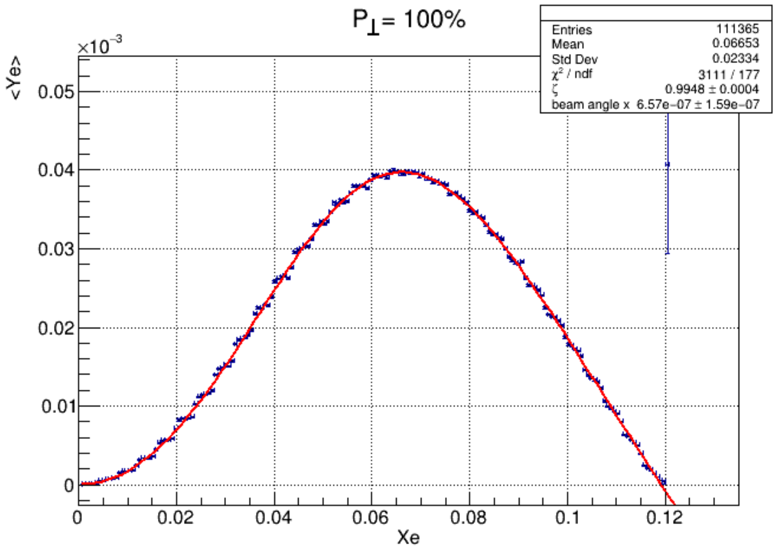
Polarization Measurement via Compton Polarimeter

- About the statistics error and fit range

	Entries	Fit range	Fit result
	Entries = 2E7	[0.00 , 0.12]	0.9964 ± 0.0014
P =100%	Entries = 2E7	[0.04 , 0.10]	0.9981 ± 0.0016
	Entries = 2E8	[0.00 , 0.12]	0.9948 ± 0.0004







- For statistic error, 0.15% for 2E7, 0.04% for 2E8.

? The deviation between the fitting result and the true value: ①The value of the <Y> is obtain by each bin; ②smear due to detector resolution

Polarization Measurement via Compton Polarimeter

- The luminosity for continuous lasers

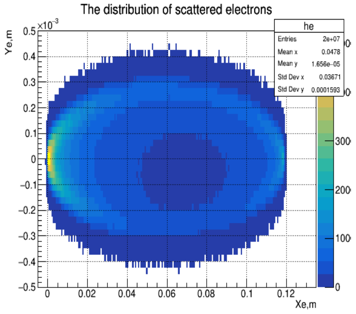
$$\mathfrak{L} = \frac{1+cos\theta_0}{\sqrt{2\pi}} \frac{I_e}{e} \frac{P_L\lambda}{hc^2} \frac{1}{\sqrt{\sigma_e^2+\sigma_\gamma^2}} \frac{1}{sin\theta_0} \approx \frac{2}{\sqrt{2\pi}} \frac{I_e}{e} \frac{P_L\lambda}{hc^2} \frac{1}{\sqrt{\sigma_e^2+\sigma_\gamma^2}} \frac{1}{\theta_0}$$

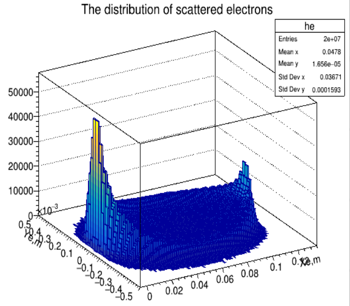
Par.	Unit	Physics meaning	CEPC(Z pole)
I_e	A=C/s	mean electron current	461mA
P_L	W=J/s	power of the laser	1.0W
λ	m	Wavelength of laser	1.002μm(1.24eV)
σ_e/σ_γ	m	Rms beam size	$\sigma_\gamma = 160\mu m$
h	J/s	Planck constant	$6.626 \times 10^{-34} J \cdot s$
c	m/s	Light speed	$3 \times 10^{8} m \cdot s$
$\mathfrak{L}$	$cm^{-2}s^{-1}$	luminosity	$2.56 \times 10^{30} cm^{-2} \cdot s^{-1}$
σ	barn	Cross section	393.5mb
Max.rate	s^{-1}	Compton scattering event rate	$1.0088 \times 10^{6} s^{-1}$

- A 5%/~10% polarization level is expected to be measured in a 20s with an relative accuracy of about 1.4%.

Polarization Measurement via Compton Polarimeter

- **About the active detector dimension**

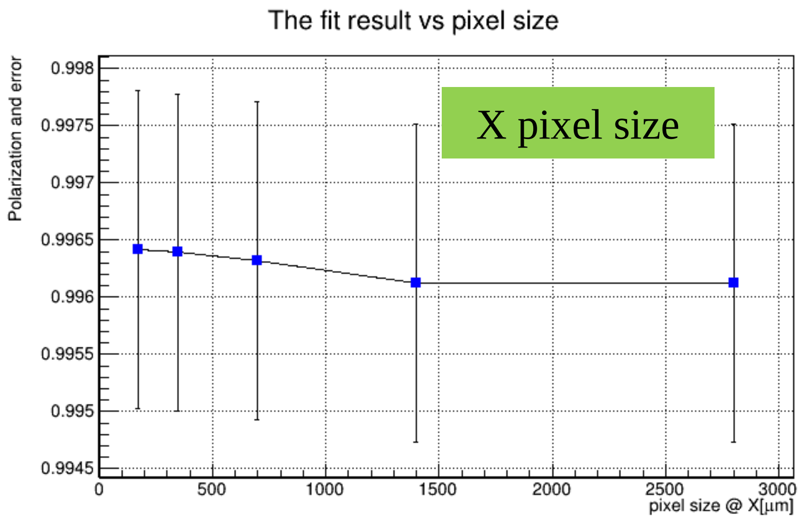


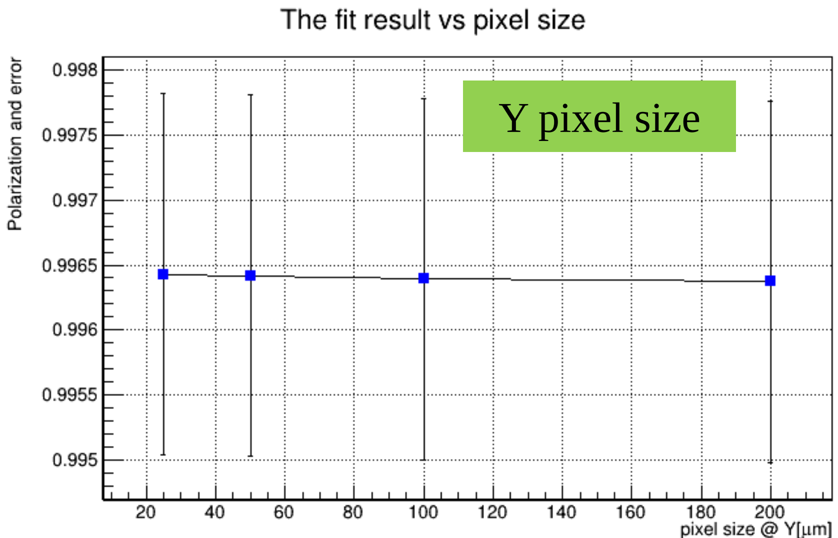


The active dimension of detector ：
$140mm \times 1mm$

The relationship between pixel size and uncertainty

X			Y		
Pixel size	number	Fit result	Pixel size	number	Fit result
175μm*25μm	800*40	0.99642±0.00139	700μm*25μm	200*40	0.99643±0.00139
350μm*25μm	400*40	0.99639±0.00139	700μm*50μm	200*20	0.99642±0.00139
700μm*25μm	200*40	0.99632±0.00139	700μm*100μm	200*10	0.99639±0.00139
1400μm*25μm	100*40	0.99612±0.00139	700μm*200μm	200*5	0.99637±0.00139
2800μm*25μm	50*40	0.99530±0.00139	***********	*****	**********





Discussion & Summary

- Compton Polarimeter is the clear technique of choice for electron polarization at CEPC
  - High precision (~1.4%) has been achieved in 20s time
  - The resolution of detector and the beam angle have been considered in our Toy MC
  - The measurement of polarization has low requirements for detector(different from calibrate the beam energy)

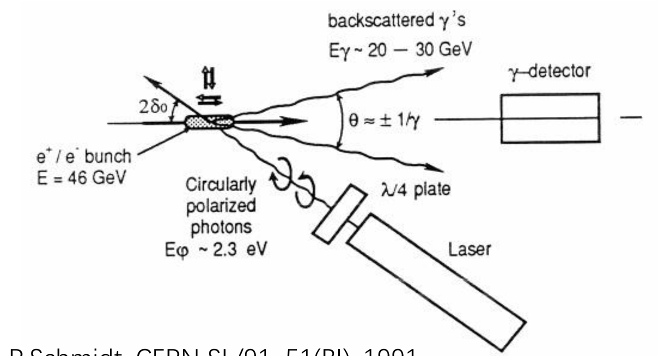
- The systematic error may be from :①the uncertainty of beam energy; ② layout of drift distance and magnet; ③ The Angle of collision between laser beam and electron beam; ④ error from detector (A full simulation by Geant4 would be desirable to study the systematics uncertainty.

- The measurement of longitudinal polarization by Compton polarimeter are going on~

Backup

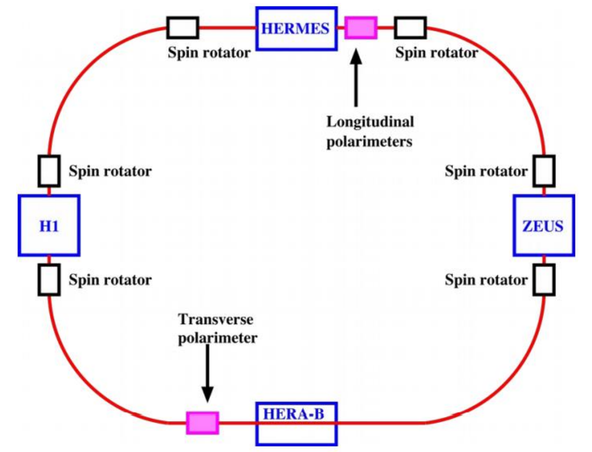
Compton polarimeter

CERN LEP 46GeV



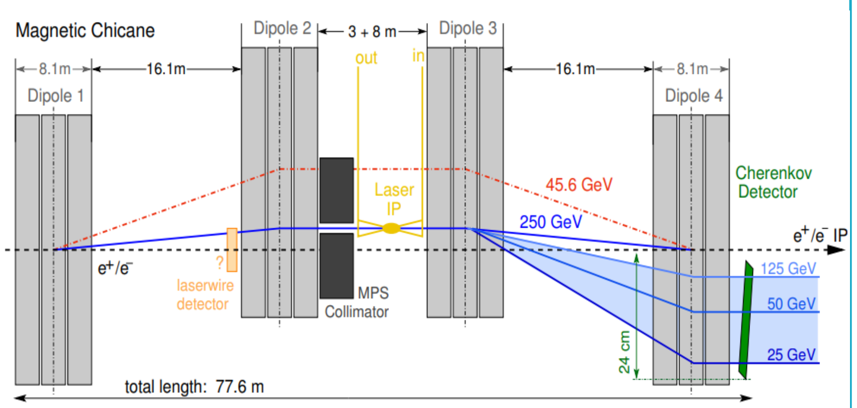
R.Schmidt. CERN SL/91-51(BI), 1991.

HERA 27GeV



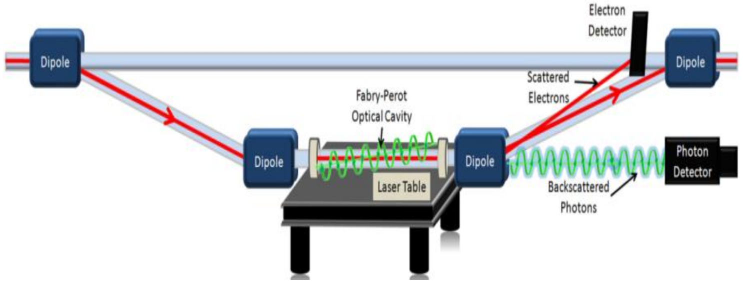
S.Schmitt, HERA polarimeter review

ILC 45.6GeV



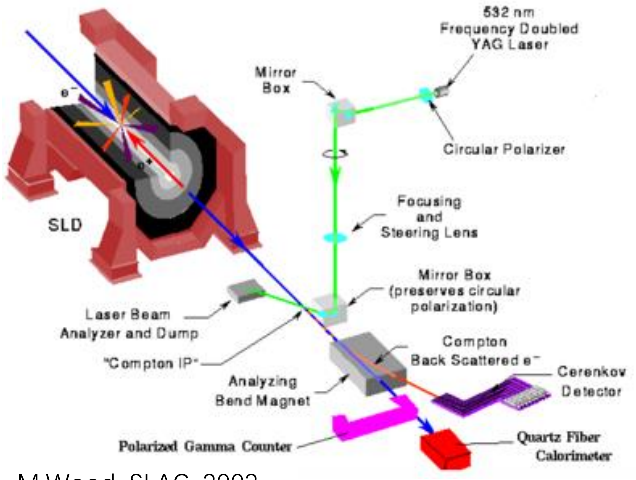
Jenny List, ILC Polarimetry,2020

JLab Hall C 1.16GeV



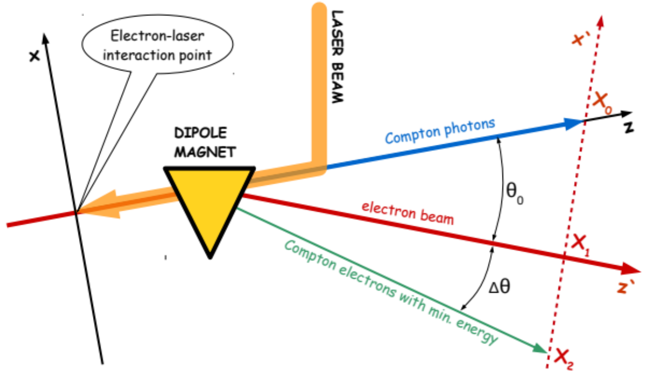
Donald Jones, Hall C Compton Polarimetry, PSTP 2013.

SLD at SLAC 45.6GeV



M.Wood. SLAC, 2003.

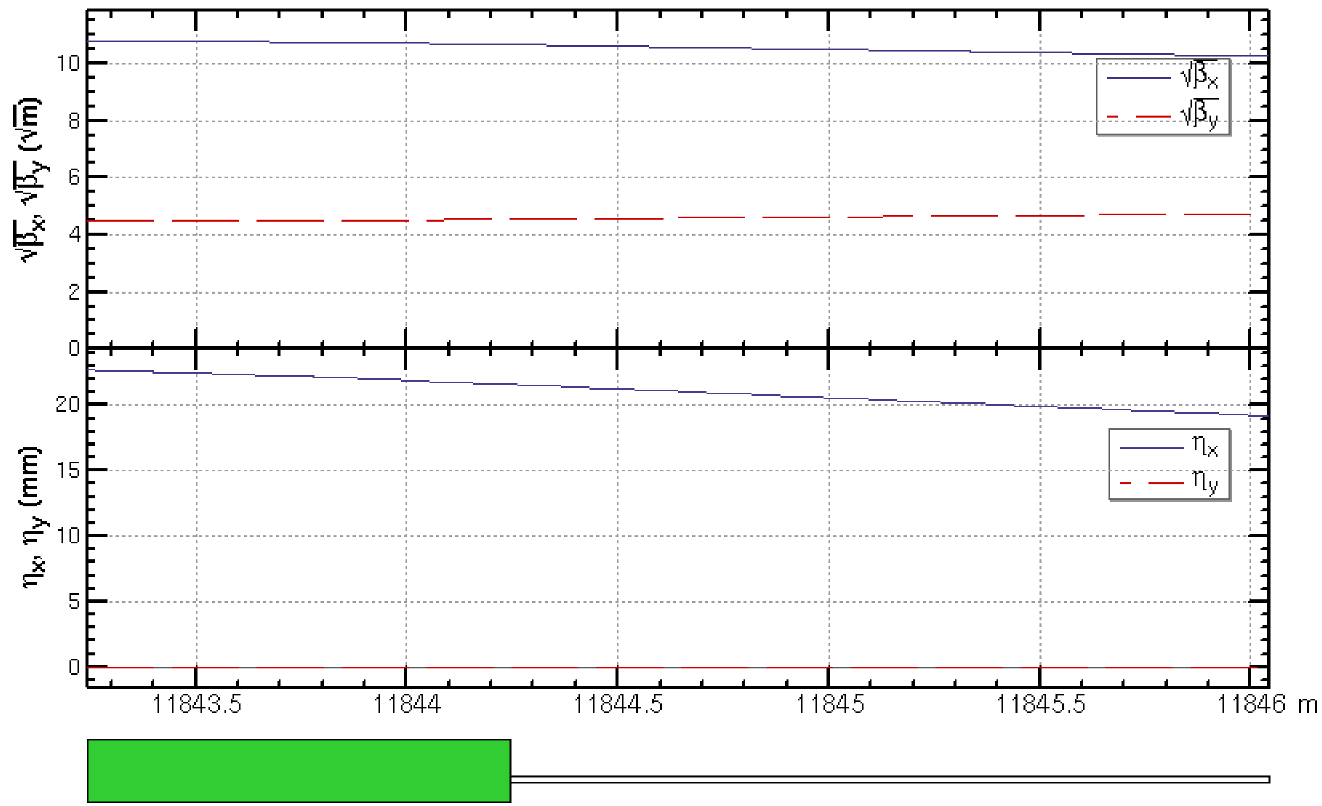
FCC-ee 45.6GeV



Nickolai Muchnoi, 2018

β function

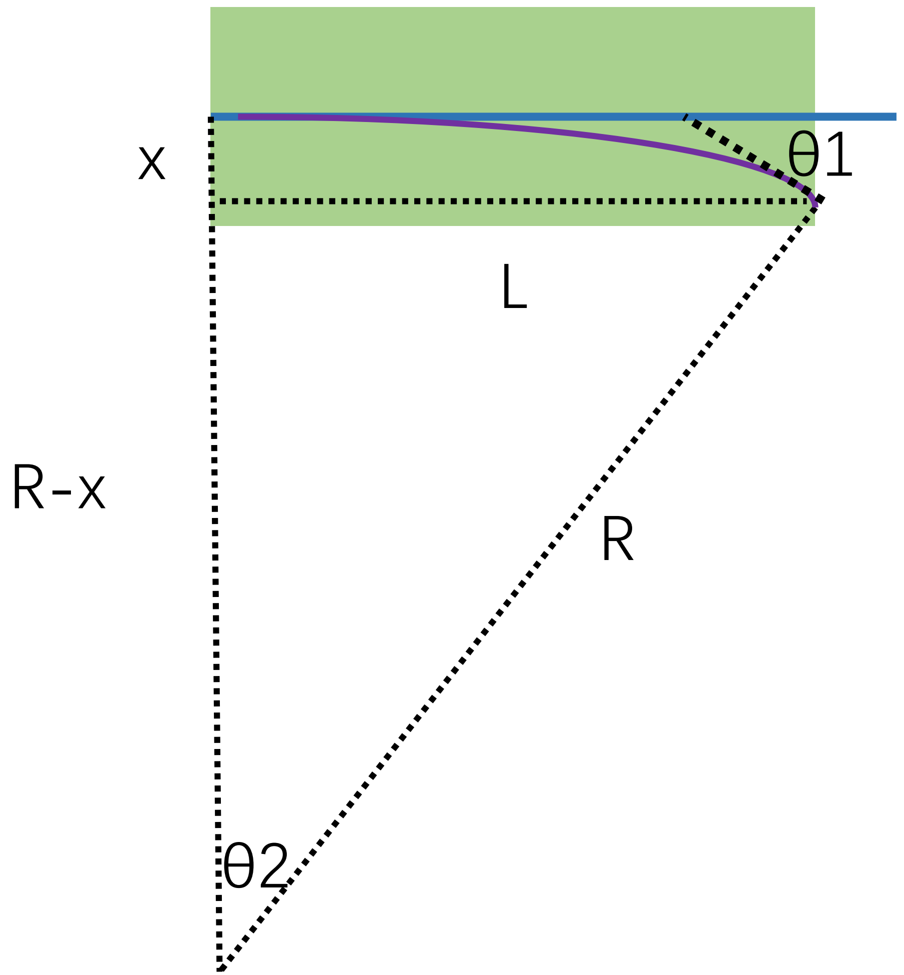
$\beta_x = 121m$
$\beta_y = 25m$



Yiwei WANG

About bending angle

- 推导偏转角和偏移量



- 偏转角等于圆心角

$bending\ angle: \theta 1 = \theta 2 = \frac{l}{R}$

- 偏移量$x: R^2 = L^2 + (R-x)^2$

- $Bqv = mv^2/R$

$E = mc^2 \rightarrow mc = E/c$

$R = \frac{mv^2}{Bqv} = \frac{mv}{Be} = \frac{E}{Bec}$

$= \frac{45.5 * 10^9 eV}{0.01867\ T \times e \times 3 * 10^8 m/s}$

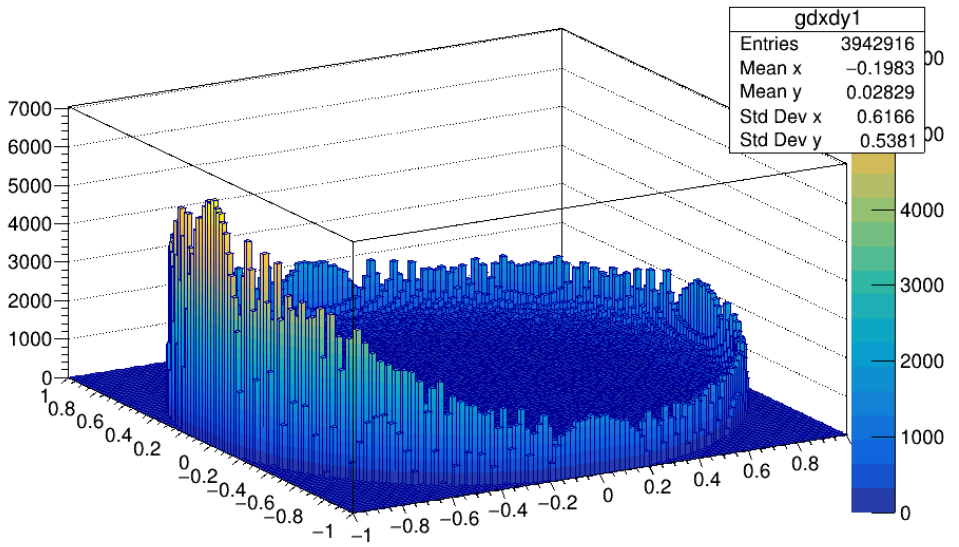
- $\theta = \frac{l}{R} = 3.4467mrad$

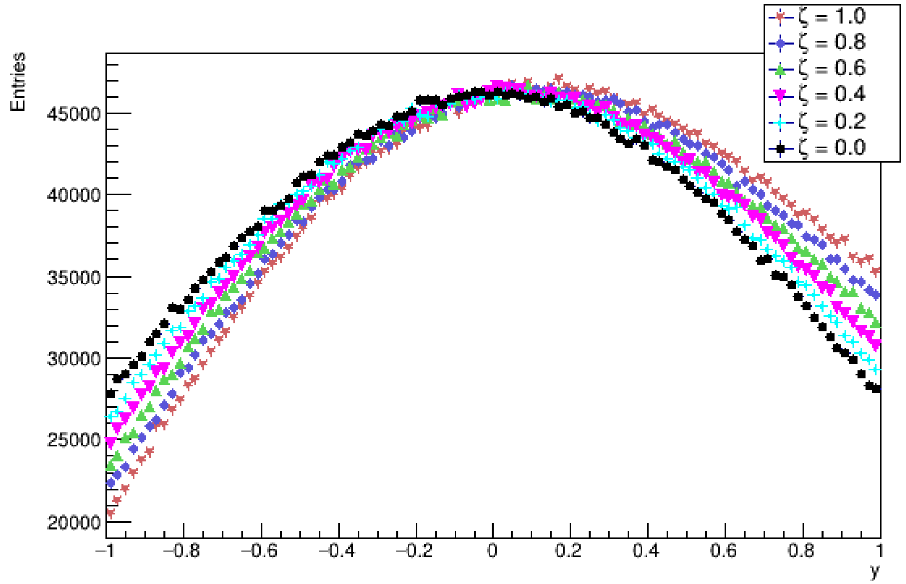
Inverse Compton scattering cross section

$$d\sigma_0 = \frac{r_e^2}{\kappa^2(1+u)^3}\left(\kappa(1+(1+u)^2) - 4\frac{u}{\kappa}(1+u)(\kappa-u)\left[1-\xi_\perp\cos\big(2(\varphi-\varphi_\perp)\big)\right]\right) du\, d\varphi,$$

$$d\sigma_\parallel = \frac{\xi_\circlearrowleft \zeta_\circlearrowleft r_e^2}{\kappa^2(1+u)^3} u(u+2)(\kappa-2u) \, du\, d\varphi,$$

$$d\sigma_\perp = -\frac{\xi_\circlearrowleft \zeta_\perp r_e^2}{\kappa^2(1+u)^3} 2u\sqrt{u(\kappa-u)}\cos(\varphi-\phi_\perp) \, du\, d\varphi.$$





Decide the dimension of detector

Laser energy

$$Xe_{max} \approx \kappa\theta_2 L_2 = \frac{4\omega_0 E_e}{m_e^2}\theta_2 L_2 = \frac{4\omega_0}{m_e^2}(lBec)L_2$$

Drift distance

Dipole length

$$Ye_{max} \approx \frac{L_1}{\gamma} \times \frac{\kappa}{2} = \frac{L_1 * \frac{4\omega_0 E_e}{m_e^2}}{2\frac{E_e}{m_e}} = \frac{2\omega_0 L_1}{m_e}$$

$\Pi(Xe)$

$$\Pi(x) = \frac{\int y \frac{d\sigma_\perp}{dxdy} dy}{\int \frac{d\sigma_0}{dxdy} dy}$$

$we\ use\ the\ y = \sqrt{1-x^2} sin\theta, \theta \in [-\frac{\pi}{2}, \frac{\pi}{2}]$

$$\int y \frac{d\sigma_\perp}{dxdy} dy = \int_{-\sqrt{1-x^2}}^{\sqrt{1-x^2}} \frac{r_e^2}{(1+u)^3\sqrt{1-x^2-y^2}} uy^2 dy = \frac{ur_e^2}{(1+u)^3} \int_{-\sqrt{1-x^2}}^{\sqrt{1-x^2}} \frac{y^2}{\sqrt{1-x^2-y^2}} dy = \frac{(1-x^2)ur_e^2}{(1+u)^3} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} sin\theta^2 dy = \frac{\pi(1-x^2)ur_e^2}{2(1+u)^3}$$

$$\int \frac{d\sigma_0}{dxdy} dy = \int_{-\sqrt{1-x^2}}^{\sqrt{1-x^2}} \frac{r_e^2}{(1+u)^3\sqrt{1-x^2-y^2}} \left(1+(1+u)^2 - 4\frac{u}{\kappa}(1+u)(1-\frac{u}{\kappa})\right) dy = \frac{\pi r_e^2 \left(1+(1+u)^2 - 4\frac{u}{\kappa}(1+u)(1-\frac{u}{\kappa})\right)}{(1+u)^3}$$

- $\Pi(x) = \frac{(1-x^2)u}{2\left(1+(1+u)^2-4\frac{u}{\kappa}(1+u)(1-\frac{u}{\kappa})\right)}$
- $x = \frac{(X_e - \sigma_x' L_1) - \frac{\kappa}{2}\theta_0 L_2}{\frac{\kappa}{2}\sqrt{(\frac{L_1}{\gamma})^2 + (\theta_0 L_2)^2}}$
- $y = \frac{Y_e - \sigma_y' L_1}{\frac{L_1}{\gamma}\frac{\kappa}{2}}$
- $u(Xe) = \frac{2(X_e - \sigma_x' L_1)\theta_0 L_2 + \kappa(\frac{L_1}{\gamma})^2}{2((\frac{L_1}{\gamma})^2 + (\theta_0 L_2)^2)}$

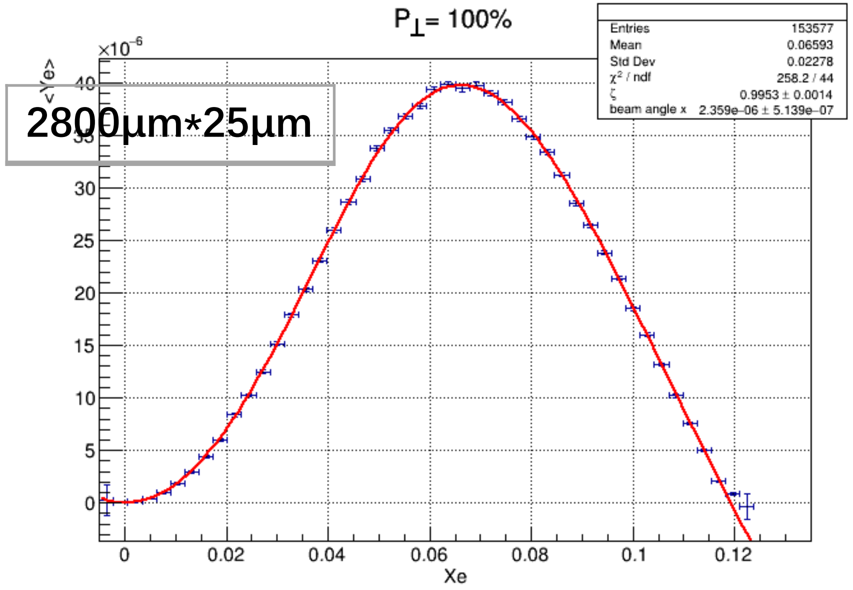
$$\Pi(Xe) = \frac{\boldsymbol{L_1}}{\boldsymbol{\gamma}}\frac{\boldsymbol{\kappa}}{\boldsymbol{2}} \frac{\left(1 - \left(\frac{(X_e - \sigma_x' L_1) - \frac{\kappa}{2}\theta_0 L_2}{\frac{\kappa}{2}\sqrt{(\frac{L_1}{\gamma})^2 + (\theta_0 L_2)^2}}\right)^2\right) u(Xe)}{2\left(1+(1+u)^2 - 4\frac{u}{\kappa}(1+u)(1-\frac{u}{\kappa})\right)}$$

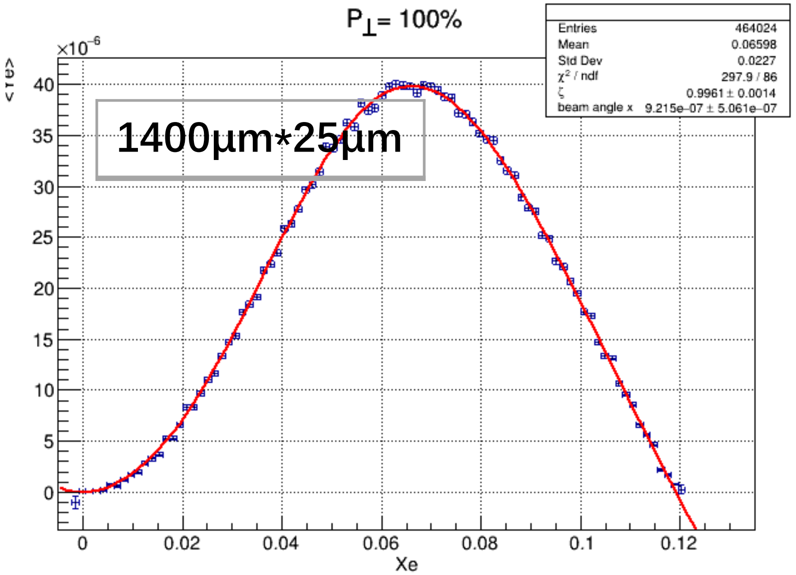
CDR

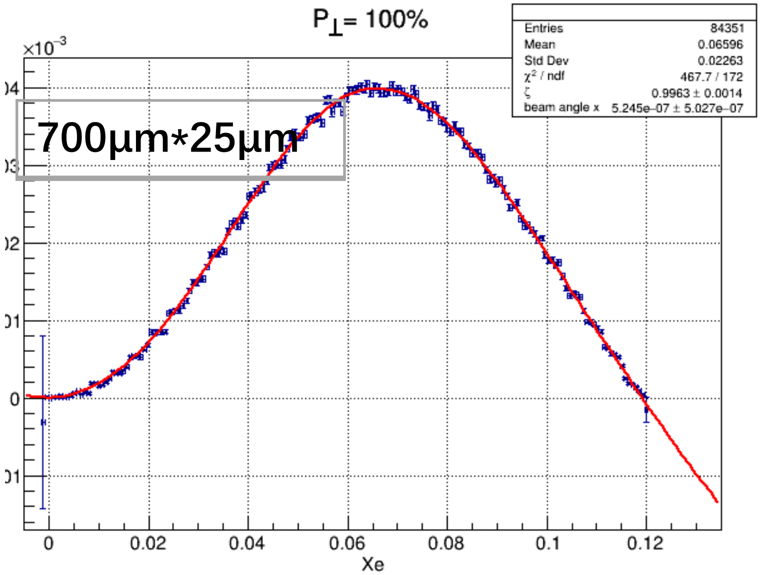
Table 4.3.3.5: Parameters of the dual aperture dipole.

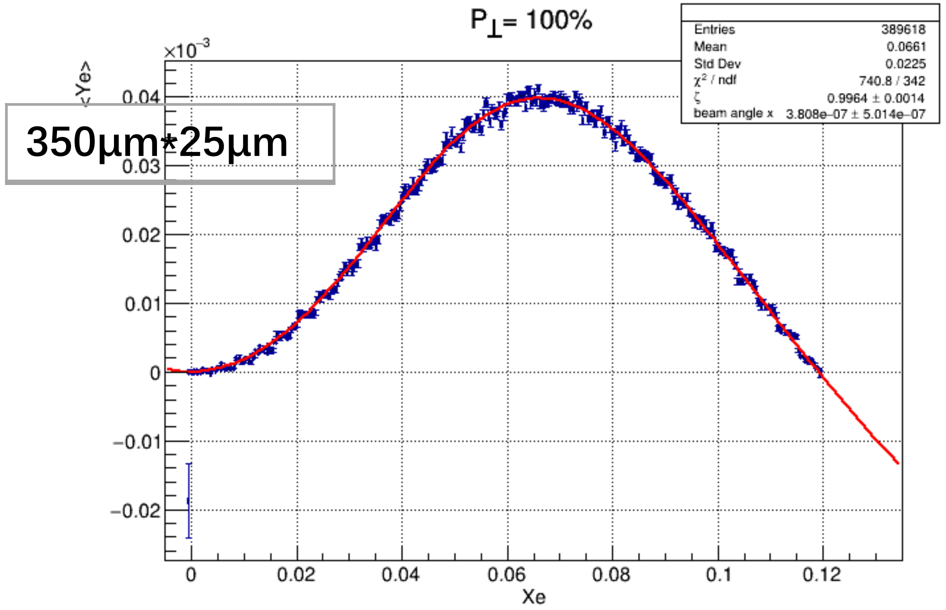
Beam center separation [mm]		350
Magnetic length [m]		28.686
Magnetic strength [Gs]		373.4
Gap [mm]		70
Coil	Number	
	Shape	
	Material	Aluminum
	Conductor specs. [mm]	30×54
Current [A]		1058
Current density [A/mm^2]		0.67
Resistance [mΩ]		2.44
Voltage [V]		2.58
Power consumption [kW]		2.73
Cooling water	Loop number	1
	Pressure drop [kg/cm^2]	6
	Velocity [m/s]	1.75
	Flux [l/s]	0.138
	Temperature rise [°C]	4.7

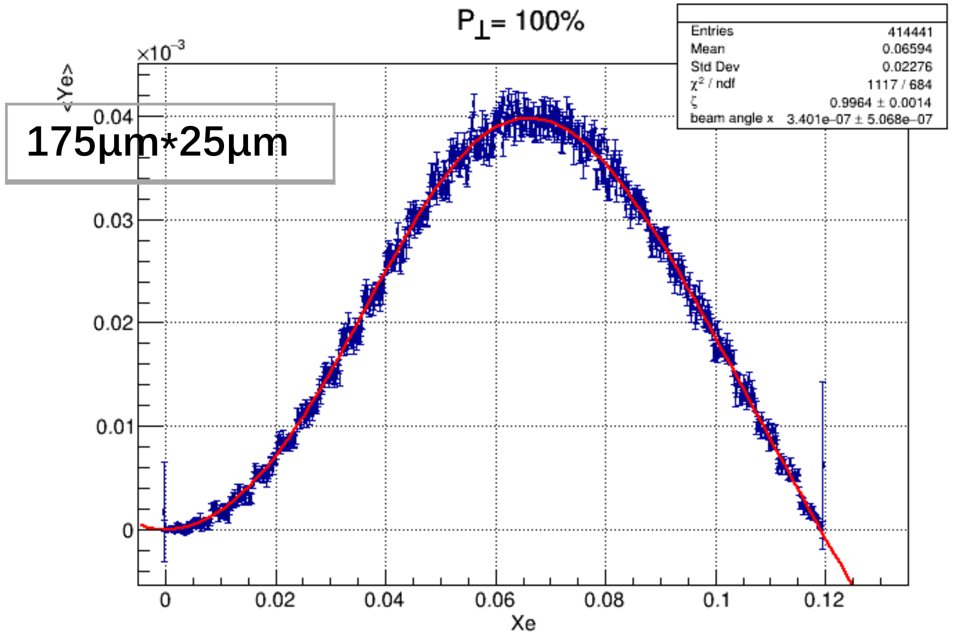
The magnetic strength of the dipole located in last is $\frac{1}{2}B = \frac{373.4Gs}{2} = 0.01867T$

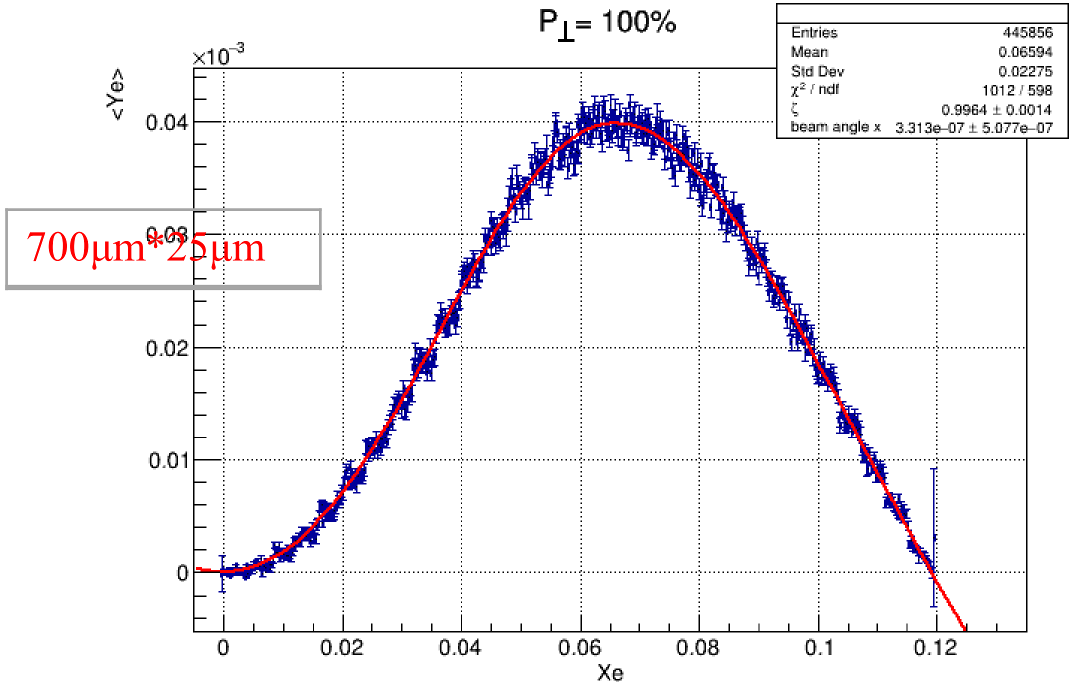

2800μm*25μm
P⊥= 100%
Entries 153577
Mean 0.06593
Std Dev 0.02278
χ² / ndf 258.2 / 44
ζ 0.9953 ± 0.0014
beam angle x 2.359e−06 ± 5.139e−07
<Ye>
×10⁻⁶
Xe

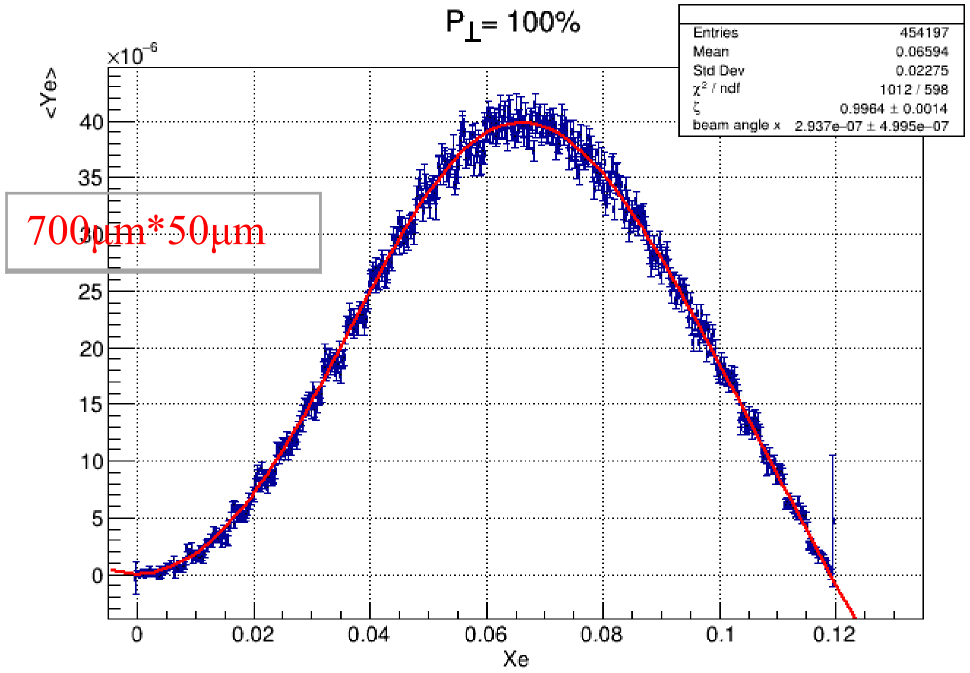

1400μm*25μm
P⊥= 100%
Entries 464024
Mean 0.06598
Std Dev 0.0227
χ² / ndf 297.9 / 86
ζ 0.9961 ± 0.0014
beam angle x 9.215e−07 ± 5.061e−07
×10⁻⁶
Xe

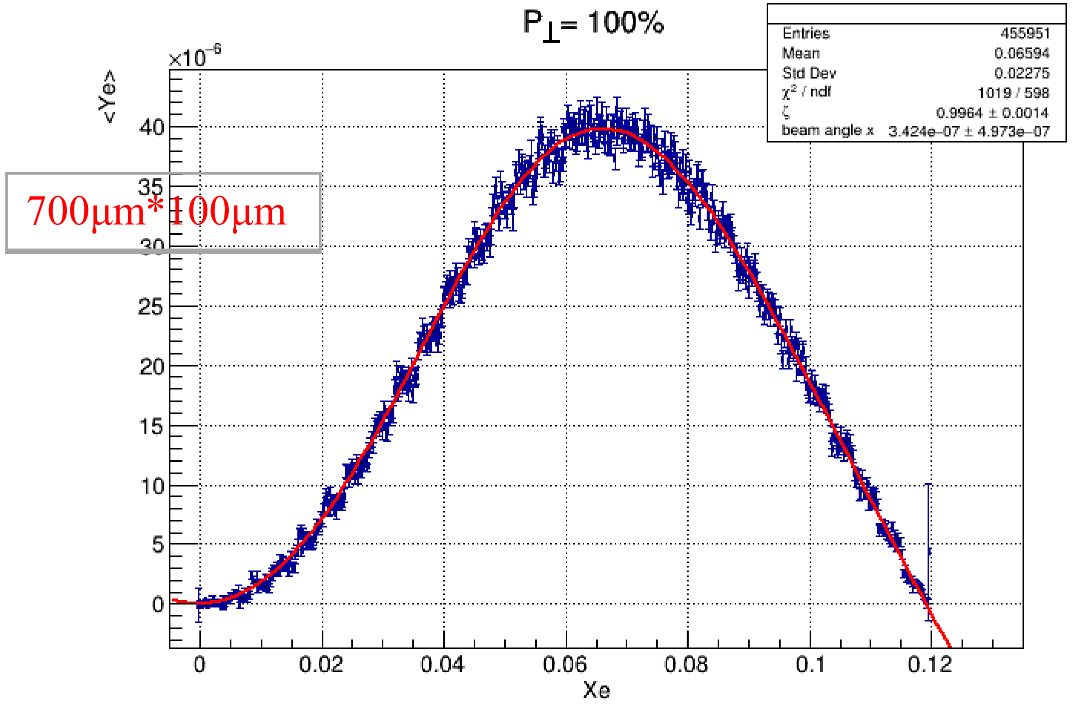

700μm*25μm
P⊥= 100%
Entries 84351
Mean 0.06596
Std Dev 0.02263
χ² / ndf 467.7 / 172
ζ 0.9963 ± 0.0014
beam angle x 5.245e−07 ± 5.027e−07
×10⁻³
Xe

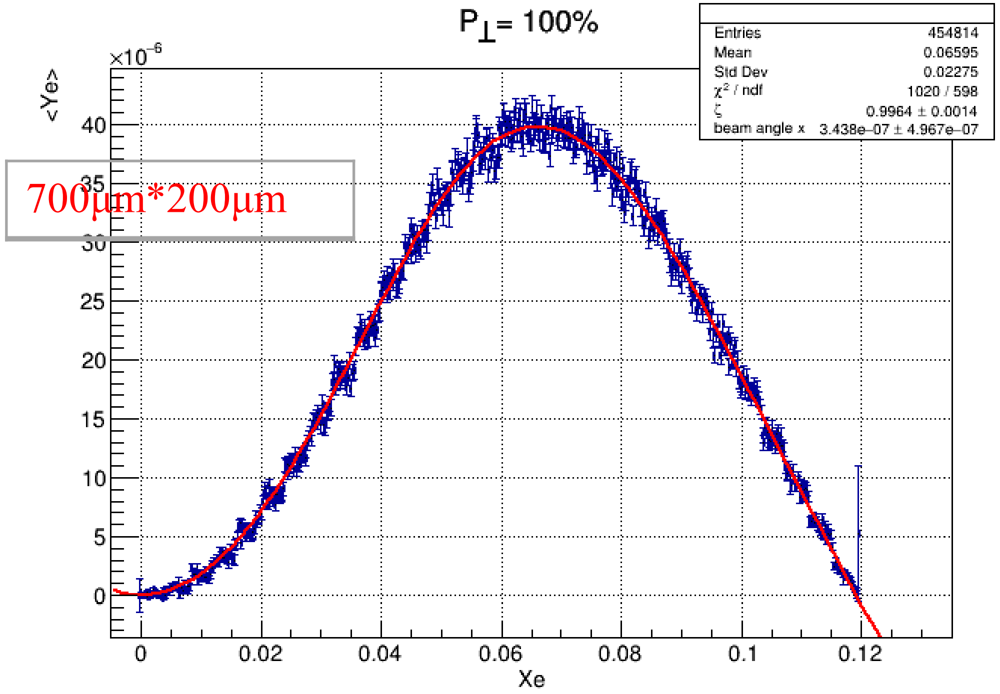

350μm*25μm
P⊥= 100%
Entries 389618
Mean 0.0661
Std Dev 0.0225
χ² / ndf 740.8 / 342
ζ 0.9964 ± 0.0014
beam angle x 3.808e−07 ± 5.014e−07
<Ye>
×10⁻³
Xe


175μm*25μm
P⊥= 100%
Entries 414441
Mean 0.06594
Std Dev 0.02276
χ² / ndf 1117 / 684
ζ 0.9964 ± 0.0014
beam angle x 3.401e−07 ± 5.068e−07
<Ye>
×10⁻³
Xe


P⊥= 100%
Entries 445856
Mean 0.06594
Std Dev 0.02275
χ2 / ndf 1012 / 598
ζ 0.9964 ± 0.0014
beam angle x 3.313e−07 ± 5.077e−07
<Ye>
×10−3
Xe
700µm*25µm


P⊥= 100%
Entries 454197
Mean 0.06594
Std Dev 0.02275
χ2 / ndf 1012 / 598
ζ 0.9964 ± 0.0014
beam angle x 2.937e−07 ± 4.995e−07
<Ye>
×10−6
Xe
700µm*50µm


P⊥= 100%
Entries 455951
Mean 0.06594
Std Dev 0.02275
χ2 / ndf 1019 / 598
ζ 0.9964 ± 0.0014
beam angle x 3.424e−07 ± 4.973e−07
<Ye>
×10−6
Xe
700µm*100µm


P⊥= 100%
Entries 454814
Mean 0.06595
Std Dev 0.02275
χ2 / ndf 1020 / 598
ζ 0.9964 ± 0.0014
beam angle x 3.438e−07 ± 4.967e−07
<Ye>
×10−6
Xe
700µm*200µm