CEPC Beam energy calibration

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On behalf of the CEPC Energy Calibration Group

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Working group and collaborations

- **IHEP:** Xinchou Lou, Yongsheng Huang, Guangyi Tang, Manqi Ruan, Jianyong Zhang, Guangpeng An, Yiwei Wang, Zhe Duan, Guanglei Xu(timing comtrol), Gang Wu(spatial alignment), Hongbo Zhu (Si detector), Shanhong Chen, Meiyu Si
- **CIAE:** Naiyan Wang(Compton scattering system design), Baozhen Zhao(laser system), Xiaofeng Xi (time synchronization)
- **China West Normal University**: Xiaofei Lan, (simulation of the Cherenkov radiation, the simulation of new fiber detector)
- **University of Science and Technology of China:** Shubin Liu, Changqing Feng(electronic system and test)
- **CERN factory & CIVIDEC:** CEO, CVD diamond detector and test
- **Wuhan University**: Yuan Chen(Magnetic design)

Outline

1 Configuration of CEPC/FCC

2 Laser-Compton scattering method

3 Microwave-Compton scattering method

Configuration of beam-energy calibration system @ CEPC

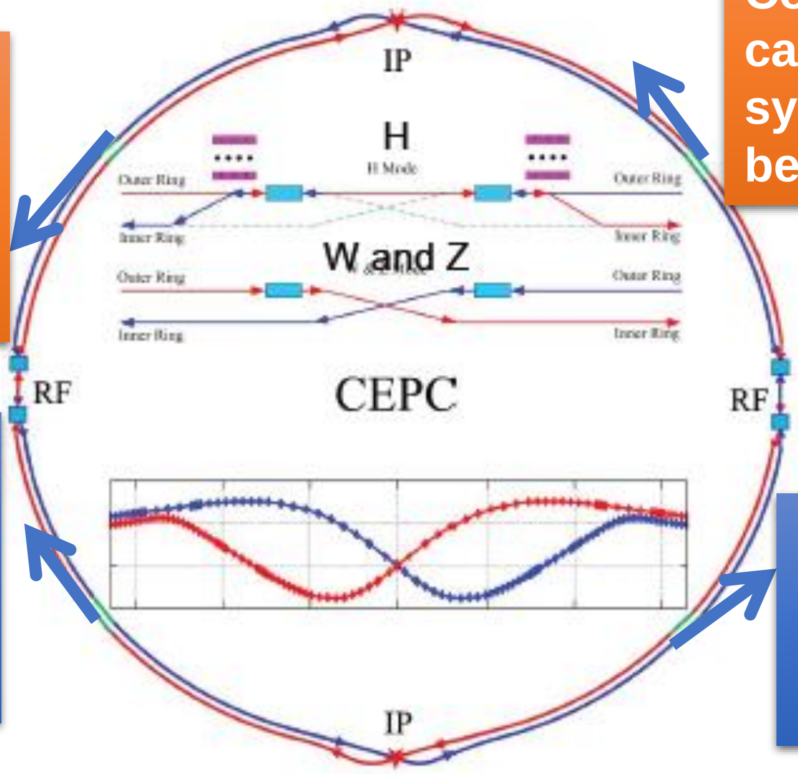
Laser-Compton Scattering method

Microwave-Compton scattering method

γSR beamline and applications

Microwave-Compton beam calibration system+ γSR beamline

Laser-Compton beam calibration system & beam dump line



Microwave-Compton beam calibration system+ γSR beamline

Laser-Compton beam calibration system & beam dump line

CEPC collider ring (100km)

Outline

1 Configuration of CEPC/FCC

2 Laser-Compton scattering method

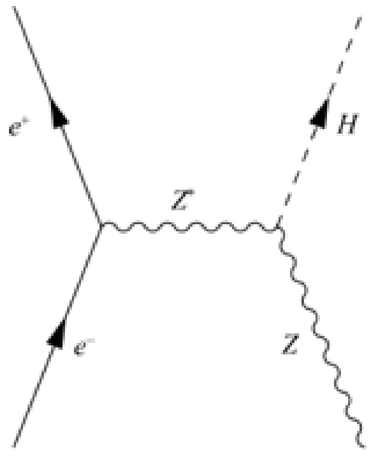
- Motivation and requirement
- Configuration
- Principle
- Simulation & Results

3 Microwave-Compton scattering method

Motivation & Requirements for beam energy

➢ Motivation

- The mass & the width of Z/W boson can be measured at CEPC *Z* pole and *W* threshold scans runs.
- The dominant systematic is expected to come from beam energy measurements.



(a)

Recoil mass method

$$e^+e^- \rightarrow ZH$$

$$m_H^2 = \left(\sqrt{s} - E_{l\bar{l}}\right)^2 - p_{l\bar{l}}^2$$

- The measurement of the ZH production cross section and the Higgs boson using the recoil mass method.
- The beam energy is an input parameter to perform measurements of the Higgs properties

➢ Requirements

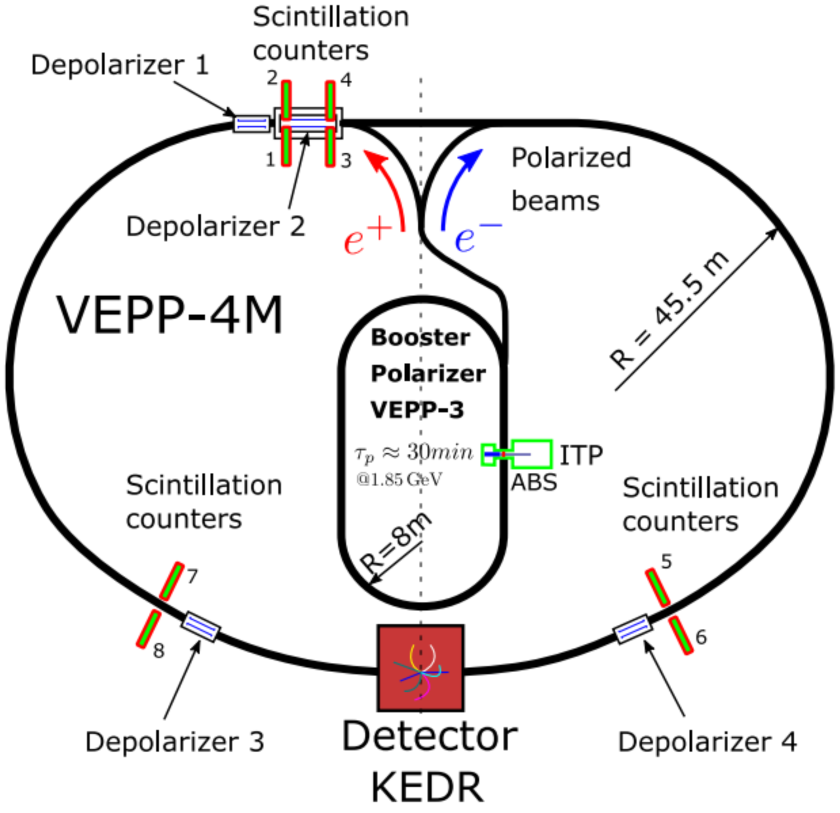
- The CEPC physics program requires precise determination of beam energies with an accuracy of the order of 1 MeV@ Higgs and 100 keV@Z/W.

An F et al., Chinese Physics C 43, (2019) 043002

CDR: Volume 2-Physics & Detector." arXiv preprint arXiv:1811.10545 (2018).

Resonant depolarization method

➢ **Resonant depolarization(RD) method @VEPP-4M LEP**



- Scheme of VEPP-4M complex from the view of polarization experiments.

Table: Experiment of calibrated beam energy by RD

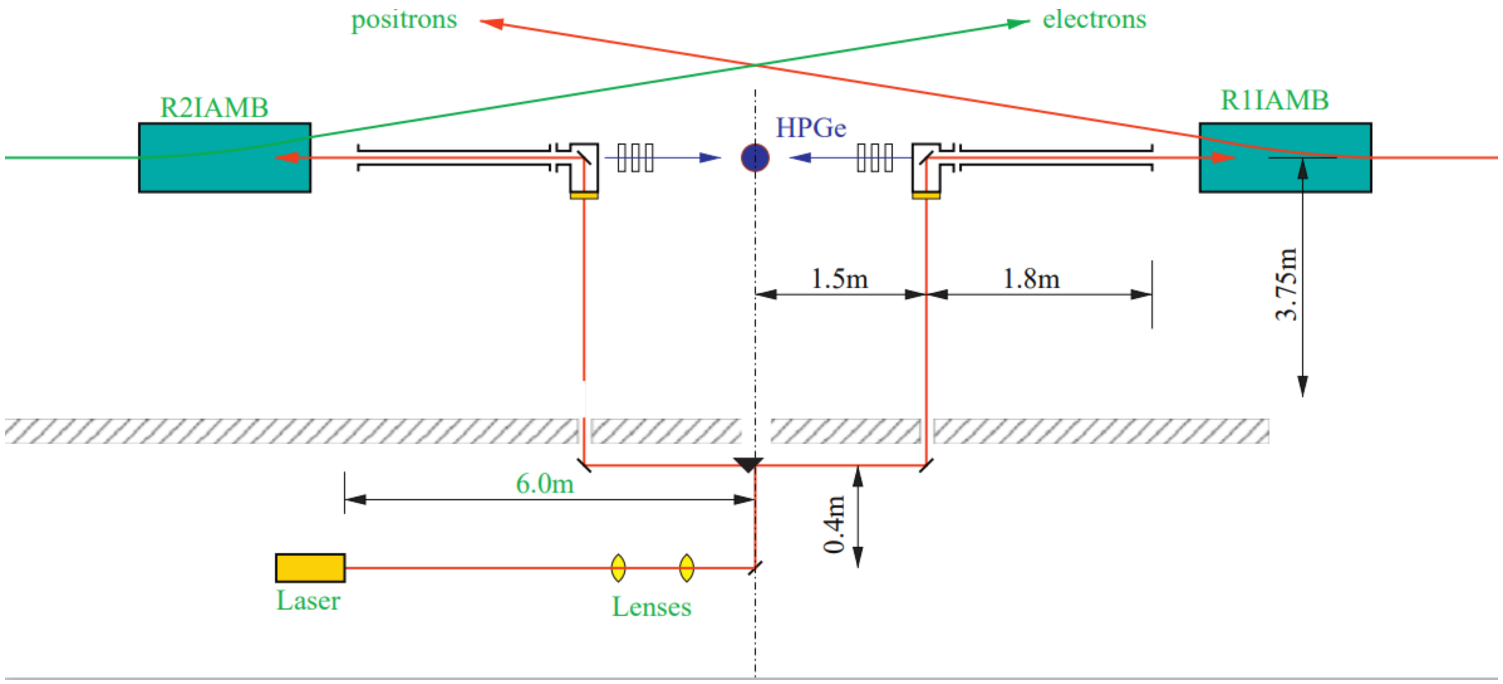
粒子	实验	时间
$\Phi, K^{\pm}$	VEPP-2M[78, 79]	1975-1979
$J/\psi, \psi(2S)$	VEPP-4 [80, 81]	1980-1981
$\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$	VEPP-4[82--86]	1982-1986
K^0, ω	VEPP-2M CMD [93]	1987
Z	LEP [87]	1993
$J/\psi, \psi(2S), \tau, D^0$	VEPP-4M[89--92]	2003-2015

- The resolution is achieved in VEPP-4M is 1e-6.
- CEPC, achieving the required beam polarization of at least 5% to 10% for RD in the Higgs mode may be challenging.

The beam energy measurement system for the Beijing electron-positron collider

➢ **Compton Back Scattering method(CBS) @VEPP-4M BEPCⅡ VEPP-2000**

$$E_{beam} = \frac{E_\gamma}{2}\left[1 + \sqrt{1 + \frac{m_e^2}{\varepsilon_\gamma E_\lambda}}\right]$$

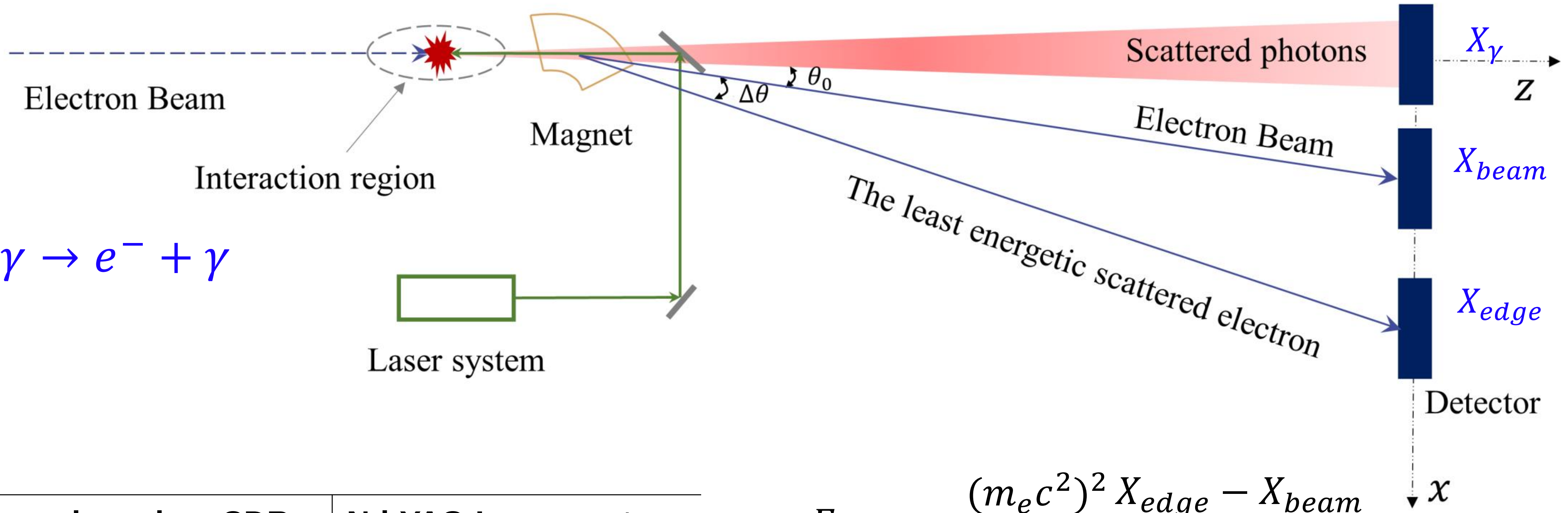


- Measuring the energy of the scattered photons (E_γ) by HPGe detector.
- The relative systematic uncertainty of the electron and positron beam energy determination is estimated as 2×10^{-5}.

CEPC beam energy calibaration

➢ Method: the electron beam distribution after Compton back-scattering combining a bending magnet

$$e^- + \gamma \rightarrow e^- + \gamma$$



Electron beam based on CDR		Nd:YAG Laser system	
Energy (GeV)	120	λ(nm)	532
N_e	15× 10^{10}	Energy(J)	0.1
Collision angle α		~ 2.35 mrad	
Compton scattering cross section		202 mb	

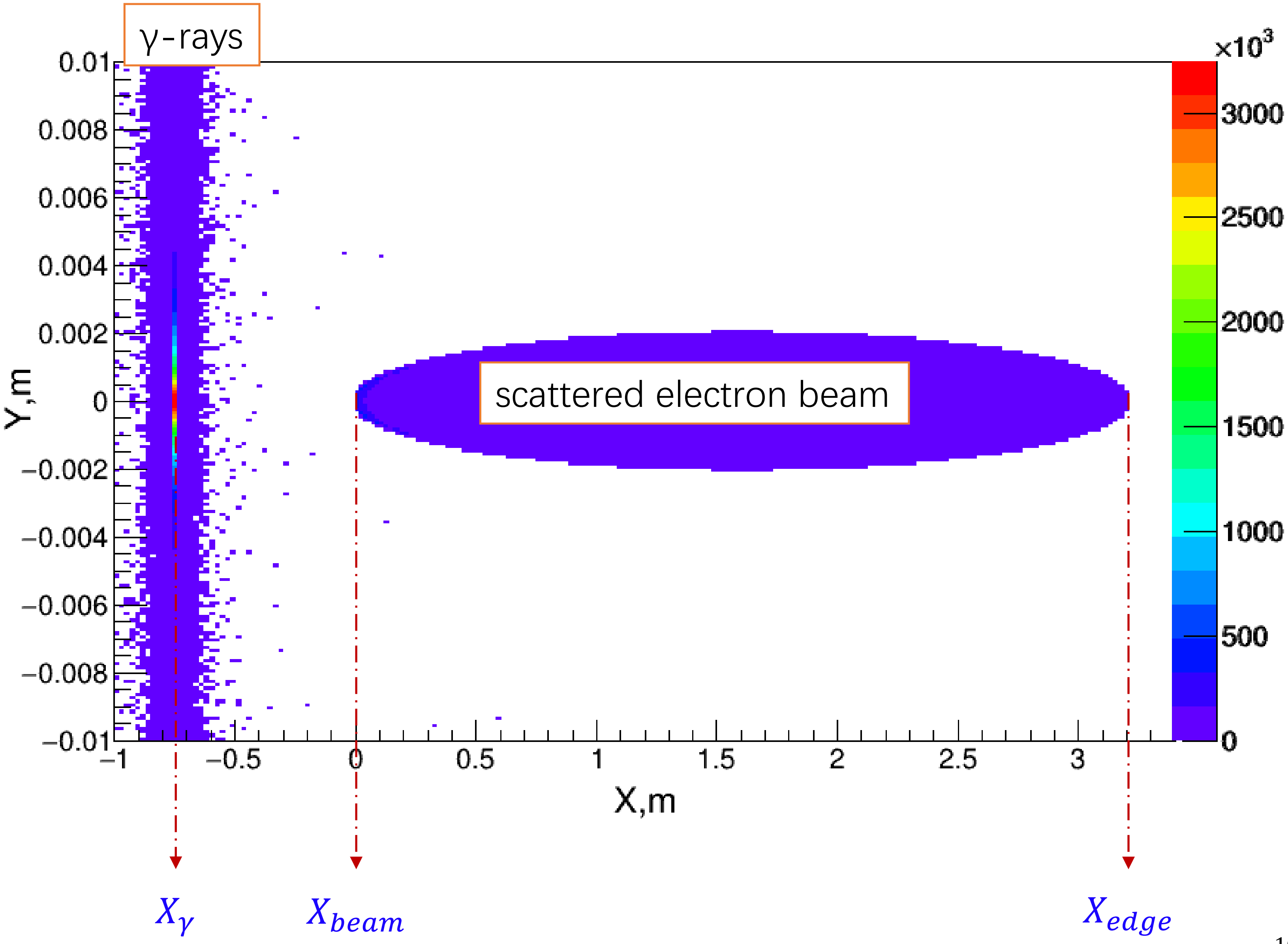
$$E_{beam} = \frac{(m_e c^2)^2}{4w_0} \frac{X_{edge} - X_{beam}}{X_{beam} - X_\gamma}$$

- The technique is “non-destructive”:
  - ~1/10000 Compton scattered particles in one collision.

Spatial distribution of scattered particles

- Beam energy can be calibrated by:
  - Position of the main electron beam particles(X_{beam}).
  - Position of scattered photons(X_γ).
  - Position of the scattered electrons with the least energy(X_{edge}).

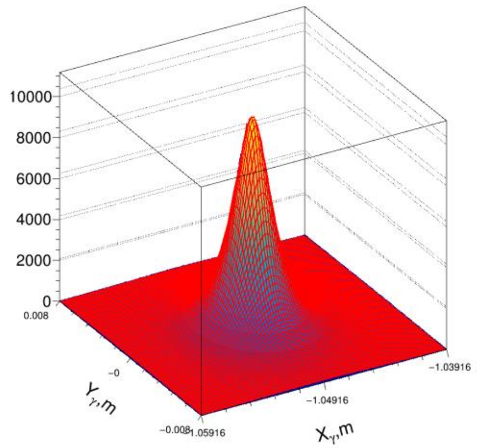
$$E_{beam} = \frac{(m_e c^2)^2}{4w_0} \frac{X_{edge} - X_{beam}}{X_{beam} - X_\gamma}$$

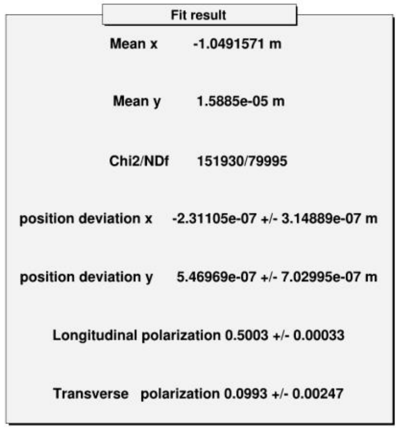


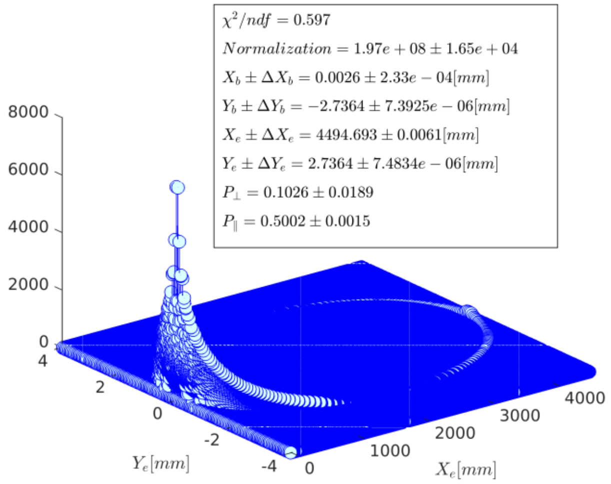
arXiv:1803.09595, 2018.

Statistical error

- Tens of seconds of data taking is necessary to achieve accuracy < 1 MeV@Higgs mode.







IP-Detector distance	100 m	200 m	300 m
Pixel size	$100\mu m \times 50\mu m$	$500\mu m \times 100\mu m$	$2mm \times 200\mu m$
$X_\gamma + \Delta X_\gamma[mm]$	-299.762±8.905$\times 10^{-5}$	-674.460±4.475×10^{-5}	-1049.16±1.134$\times 10^{-4}$
$X_{beam} + \Delta X_{beam}[mm]$	-0.0011±1.8492×10^{-4}	-0.0009±7.3215$\times 10^{-4}$	-0.0015±0.0018
$X_{edge} + \Delta X_{edge}[mm]$	1284.1928±0.0037	2889.4319±0.0132	4494.6437±0.0314
$E_b[GeV]$	119.9999	120.0003	119.9991
$\Delta E_b[MeV]$	0.356	0.573	0.875

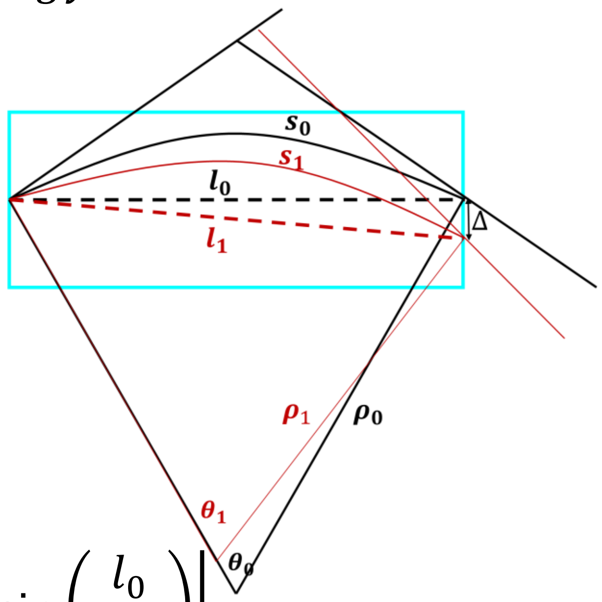
Systematic deviation

$$E_{beam} = \frac{(m_e c^2)^2}{4w_0}\frac{\Delta\theta}{\theta_0} = \frac{(m_e c^2)^2}{4w_0}\frac{X_{edge} - X_{beam}}{X_{beam} - X_\gamma} + \mathcal{O}$$

$\Delta\theta$ *is the angle between the main beam and the scattered beam of min. energy*

θ_0 *is the bending angle of BM*

$\mathcal{O}$ denotes the systematic deviations



(1) $\frac{\Delta\theta}{\theta_0}$ and $\frac{tan\Delta\theta}{tan\theta_0}$

- $\Delta E = 9.75 \pm 0.04$ MeV for a magnet with a magnetic field strength of 0.5 T (deviation is 0.2%) and length is 3 m.

(2) Differences in trajectory for different energies

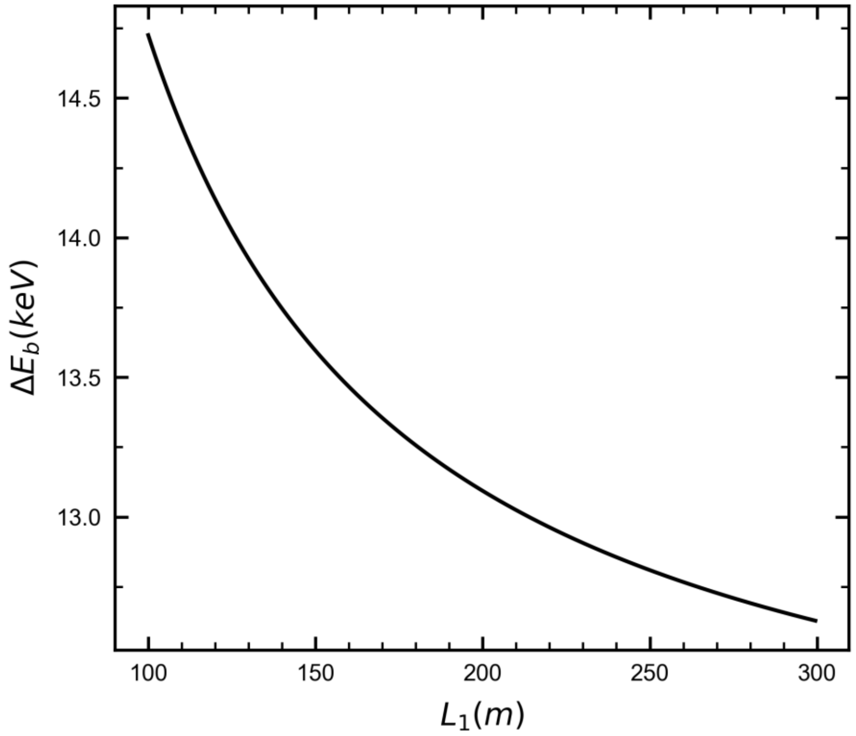
$$\Delta s = |s_1 - s_0| = \left|2\rho_1 \arcsin\left(\frac{l_1}{2\rho_1}\right) - 2\rho_0 \arcsin\left(\frac{l_0}{2\rho_0}\right)\right|$$

- Particles of different energies have different trajectories in the BM $\rightarrow$ $\Delta E = 5.76\ MeV$

Systematic uncertainty

- Considering the measurement of magnet strength and drift distance.
- The relative error is assumed to be $\Delta B/B \approx 10^{-4}$ and $\Delta L/L \approx 10^{-4}$
- The systematic uncertainties is about 20 keV

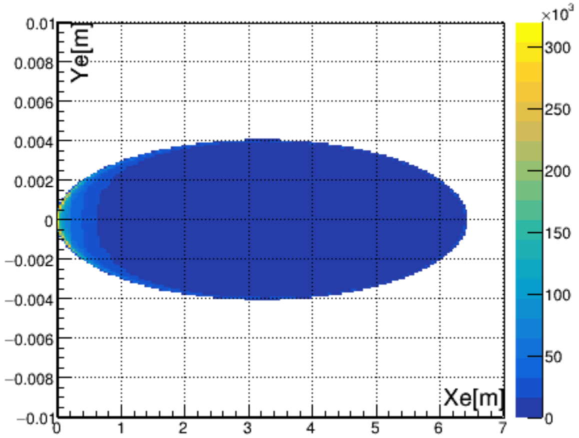
$$\Delta E = \sqrt{{\Delta E_B}^2 + {\Delta E_L}^2}$$



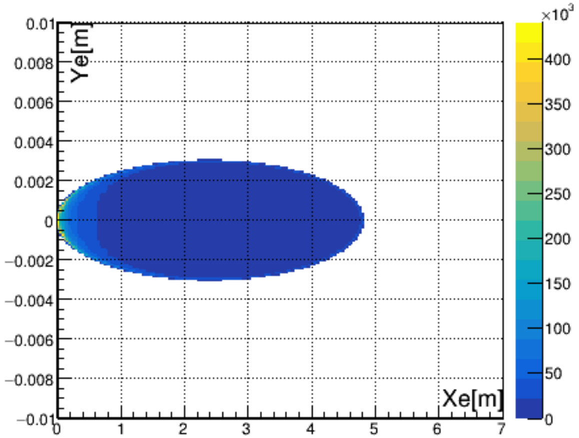
- More systematic error sources need to be considered.
- Extrapolating the center-of-mass energy needs to be discussed later.

The choice of the laser parameters

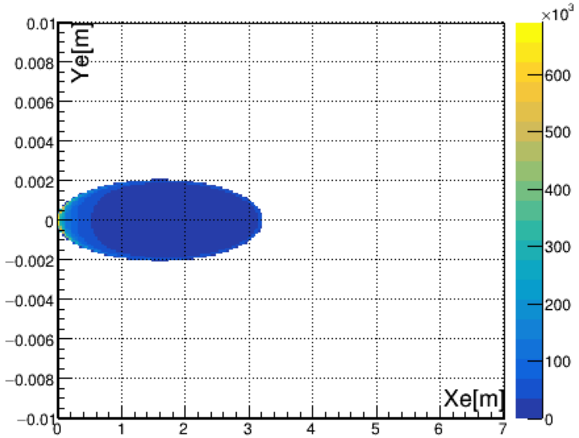
- The distribution of scattered electrons



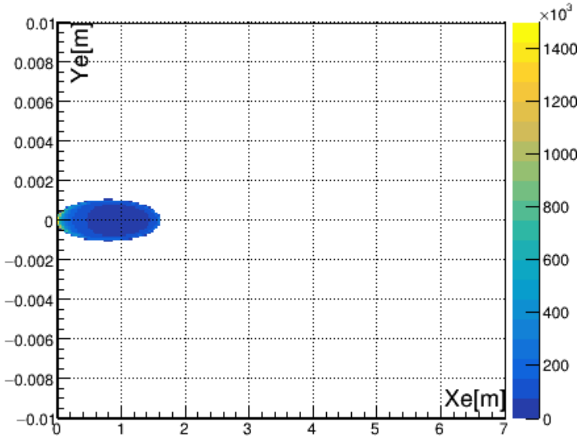
$\lambda = 256\ nm$



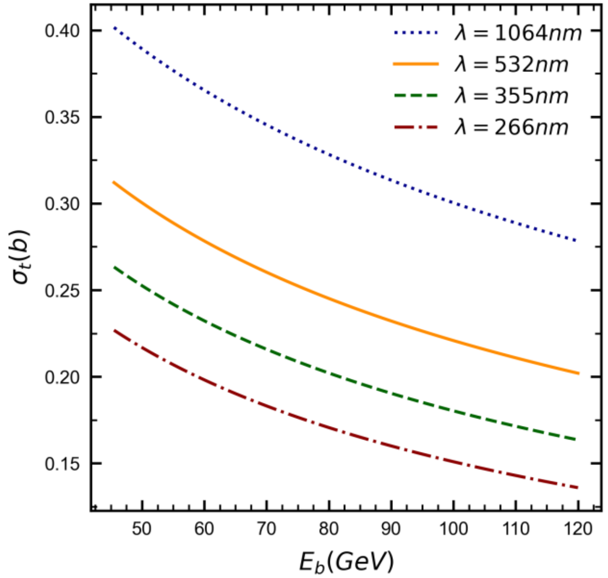
$\lambda = 355\ nm$



$\lambda = 532\ nm$



$\lambda = 1064\ nm$



- (1) Restrictions on the photon energy:

$$\frac{\delta E_{beam}}{E_{beam}} = \frac{\delta \omega_0}{\omega_0} = 8.3 \times 10^{-6}$$

- (2) Restrictions on the photon wavelength:
  - To reduce drift distance :
    - Short wavelength laser(532 nm → 266 nm)
    - Dipole length shorten (combining the system layout)

Comparison of the key parameters for different models in CEPC

Guangyi Tang

	Higgs mode	**Z mode**	**WW scan**	**$t\bar{t}$ scan**
E_{beam}/GeV	120	45	80	175
X_{edge}/m	6.16352	9.29686	7.10343	5.52276
X_{beam}/m	1.87935	5.00178	2.81903	1.28868
$\delta X_{edge}/m$	2.6×10^{-5}			
$\delta X_{beam}/m$	6×10^{-8}			
$\delta E_{beam}/MeV$	1.0	0.3	0.6	1.8

- The statistical uncertainties of beam energy are not included here

- *https://aip.scitation.org/doi/10.1063/1.5132975*

Beam energy → the center-of-mass energy

$$< \sqrt{s} >= 2\sqrt{E_+ E_-} cos \frac{\alpha}{2}$$

- Some discussion
- More systematic error sources need to be considered.
- Extrapolating the center-of-mass energy needs to be considered.
- Potential corrections of c.m. energy
  - The correlated effects of dispersion
  - Collision offsets
  - Difference between the electron and positron beams
- Beam energy uncertainties from surroundings
  - Tidal effect → collider orbit circumference
  - Railway → magnetic field

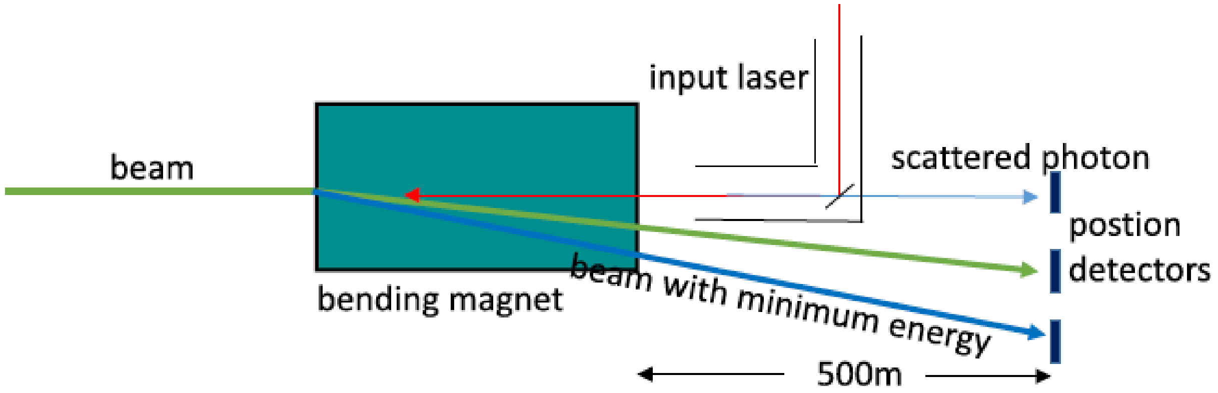
Ref: [1] arXiv preprint hep-ex/0410026, 2004. [2] Müller, Anke-Susanne. "Measurements of beam energy." (2009). [3] Alain Blondel (Geneva U. and CERN and Paris U., VI-VII)

Outline

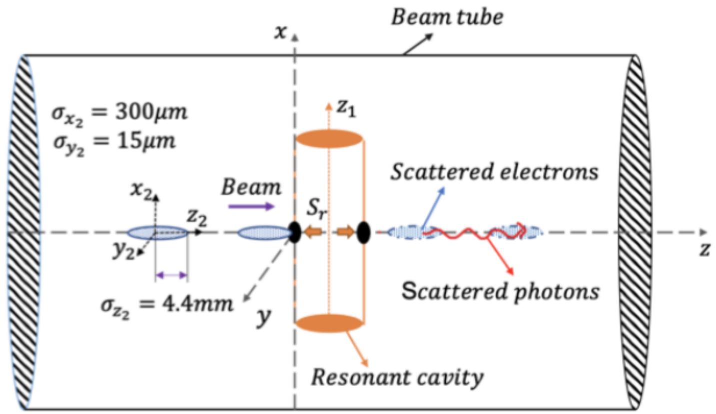
1. Configuration of CEPC/FCC
2. Laser-Compton scattering method
3. Microwave-Compton scattering method

Microwave-Compton scattering method

Laser Compton backscattering[1]



Microwave-beam Compton backscattering[2]



- Independent extraction device.
- Separately detect the positions of scattered electrons, scattered photons and unscattered beams.
- **With some proper corrections, the beam energy uncertainty of the Higgs mode is around 2 MeV.**

- Use synchrotron radiation lead wire.
- Detection of the maximum energy of scattered photons by a HPGe detector.
- **If the beam energy is calibrated within 10MeV, it will be interesting and worth doing.**

[1] Review of Scientific Instruments 91, 033109 (2020).
[2] Nuclear Inst. and Methods in Physics Research, A 1026 (2022) 166216 ,

Microwave-Compton method of calibration of beam energy

Head-to-head collision $\alpha = \pi$:

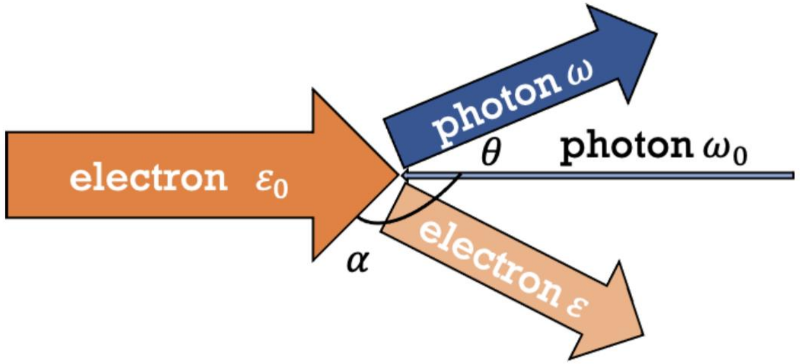


Figure 1. Compton backscattering process

Considering $\varepsilon_0 \gg m \gg \omega_0$

$$\omega_{max} = \frac{\varepsilon_0^2 sin^2(\frac{\alpha}{2}) + \frac{m^2}{4} cos\alpha}{\varepsilon_0 sin^2(\frac{\alpha}{2}) + \frac{m^2}{4\omega_0}}$$

$$\varepsilon_0 = \frac{\omega_{max}}{2}(1 + \sqrt{1 + \frac{m^2}{\omega_0 \omega_{max} sin^2(\frac{\alpha}{2})}})$$

Scattered photons:

$$\frac{dN_\gamma}{dt} = L\sigma \quad \Longrightarrow \quad \frac{dN_\gamma}{d\omega dt} = L\frac{d\sigma}{d\omega}$$

Table I. CEPC parameters in Higgs mode.

	Higgs
Beam energy ε_0 (GeV)	120
Bunch number B	242
Particles/bunch $N_2(10^{10})$	15
Bunch spacing (ns)	680
Beam current I (mA)	17.4
Bending radius ρ (km)	10.7
Beam size $\sigma_{x2}/\sigma_{y2}(\mu$m)	200-450/5-20
Bunch lengthσ_{z_2}(mm)	4.4

- **The HPGe detector has a good calibration of gamma energy within 1 to 10MeV.**
- **The energy of the scattered photons is chosen to be in the range of (8–20 MeV) compared with the synchrotron radiation background.**

Choosing $\boldsymbol{\omega_{max} = 9}$**MeV**

$\omega_0 = 4.08 \times 10^{-5}$eV $\quad \lambda = 3.04$ cm

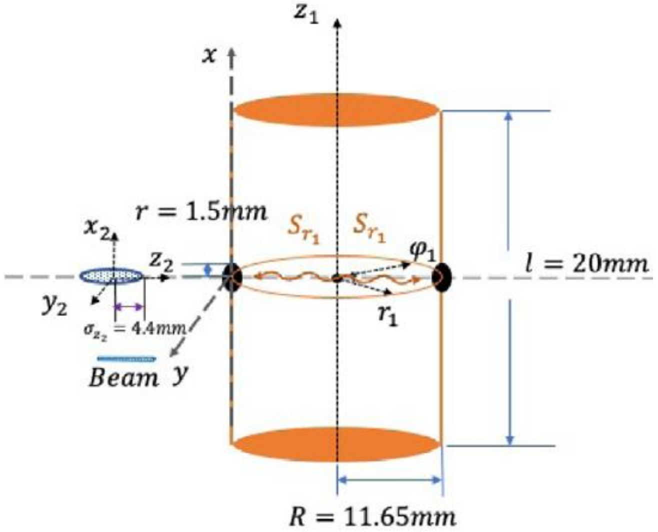
Resonant Cavity

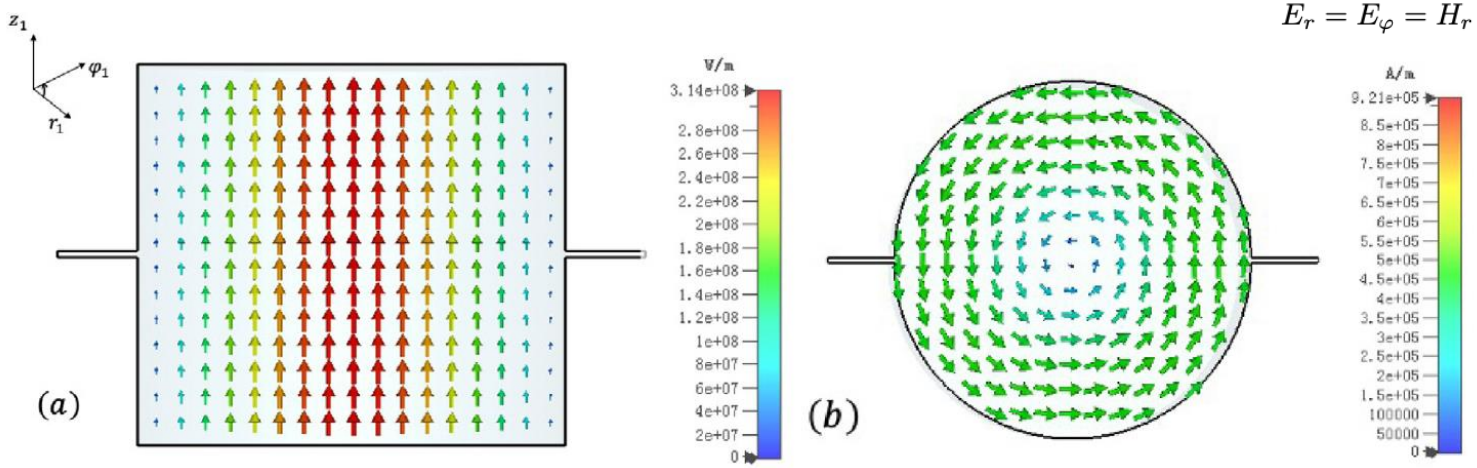
$$E_{z_1} = E_m J_0(K_c r) e^{j\omega t}$$

$$H_\varphi = jE_m \frac{1}{\eta} J_1(K_c r) e^{j\omega t}$$

$$E_r = E_\varphi = H_r = H_z = 0$$

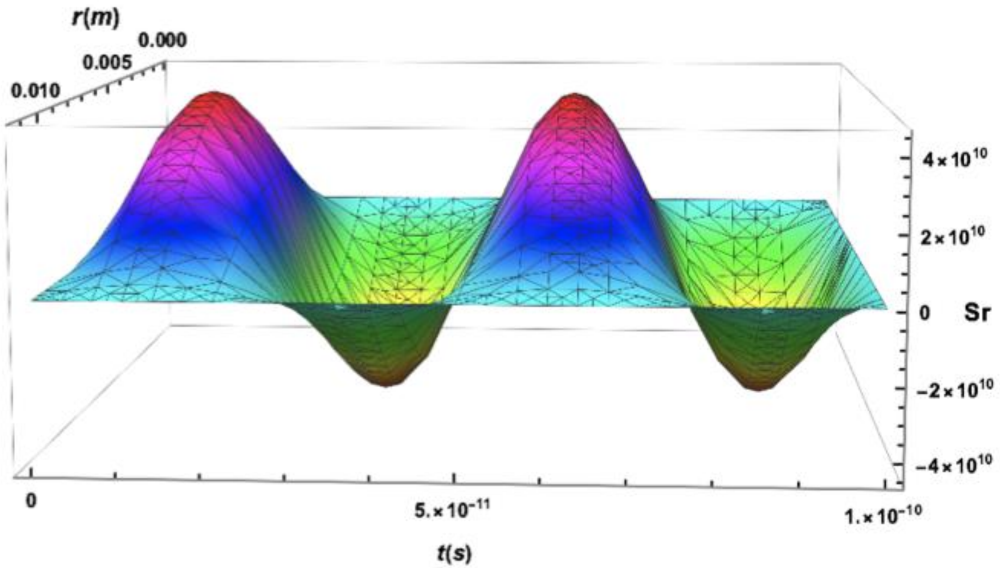
- **Choosing the TM$_{010}$ mode of the standing wave cavity:** $\lambda = \frac{2\pi}{K} = 2.613R$



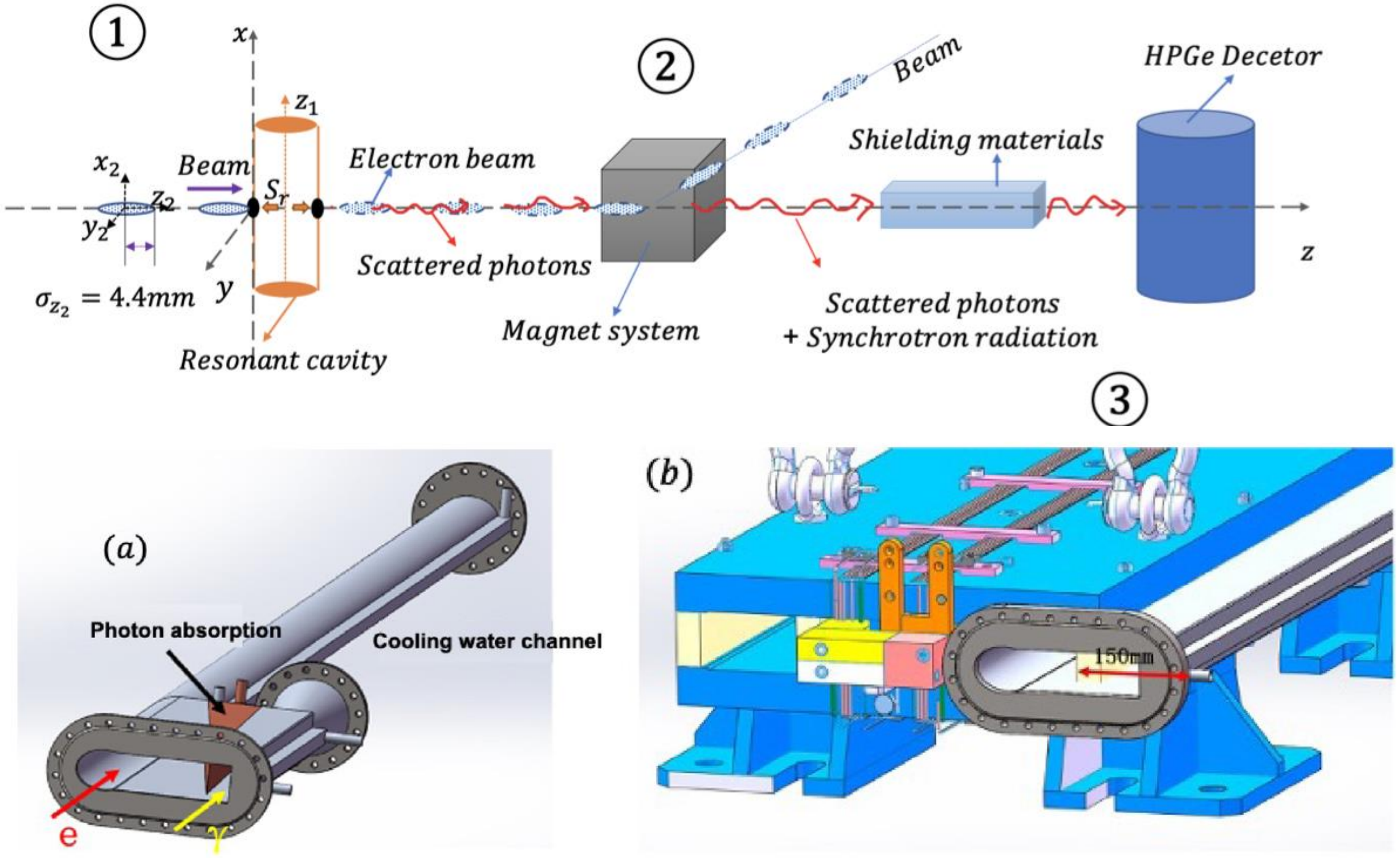


- **The Poynting vector:**

$$S_r = -E_z \times H_\varphi = \frac{E_m^2 J_0(K_c r) J_1(K_c r) sin(\omega t) cos(\omega t)}{\eta}$$



System Design

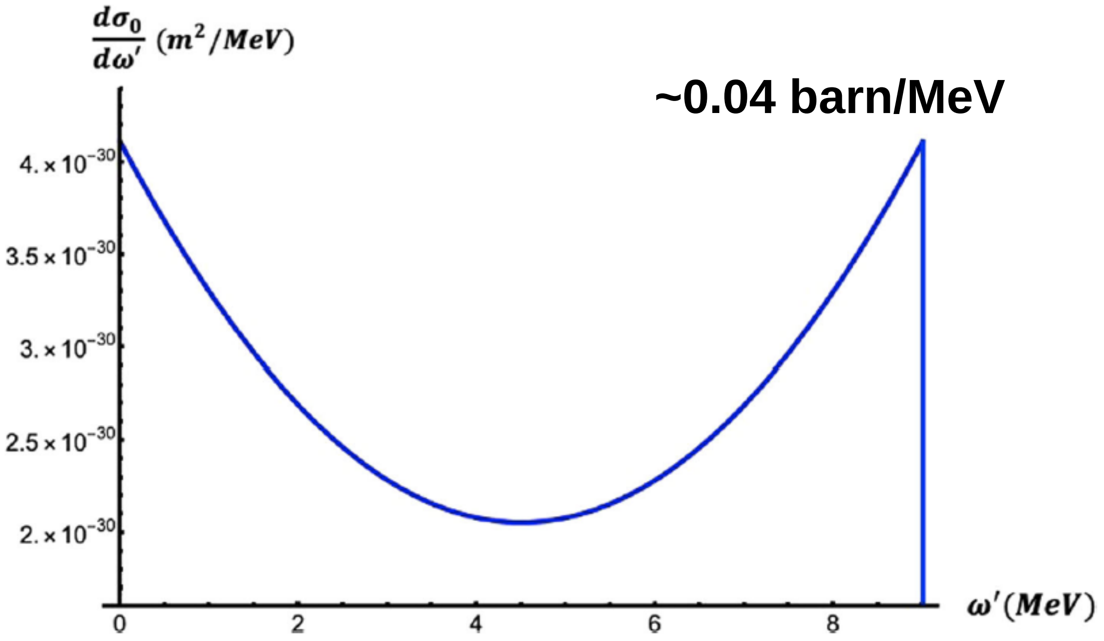


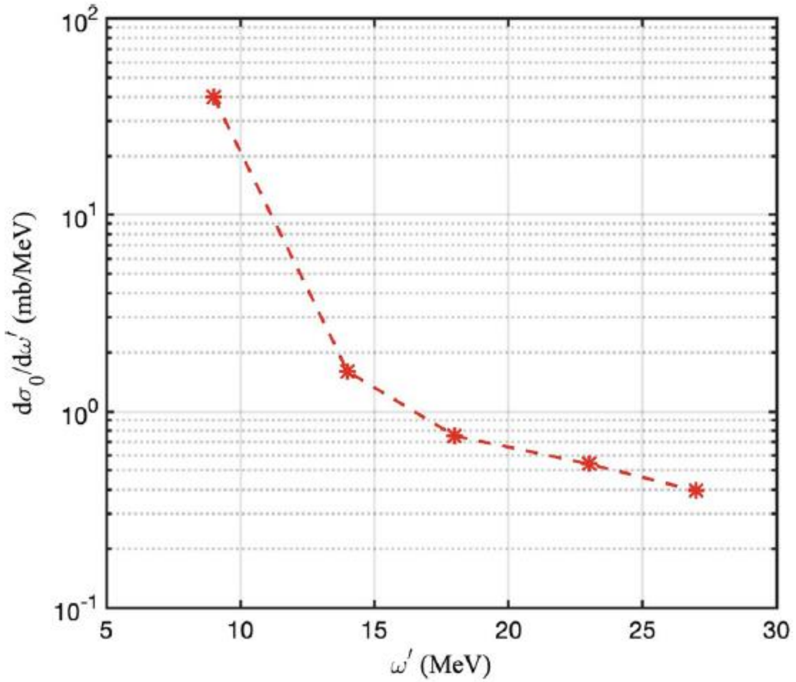
- The electrons and photons separation device designed for the beam line of the synchrotron radiation applications on CEPC.

Differential cross-section

$$\frac{d\sigma_0}{d\omega'} = \left|\mathrm{F}^{(1)}_{(\mathrm{TM}_{010})}\right|^2 \cdot 2\pi \frac{r_e^2}{\kappa^2(1+u)^3} \frac{\varepsilon_0}{(\varepsilon_0-\omega')^2} \left\{\kappa\left[1+(1+u)^2\right] - 4\frac{u}{\kappa}(1+u)(\kappa-u)\right\}.$$

$(F^{(1)}_{(TM_{010})} = \mathbf{0.608484})$





- For the microwaves with a wavelength of 3.04 cm collide head-on with 120 GeV electrons on CEPC, the maximum energy of scattered photons is $\omega' = 9$ MeV.

- The maximum energy of the nonlinear Compton scattering is $\omega' = 14$ MeV, $\omega' = 18$ MeV, $\omega' = 23$ MeV, $\omega' = 27$ MeV, corresponding to the nonlinear order 2, 3, 4, 5, respectively.

https://doi.org/10.1140/epjd/s10053-022-00389-4.

Luminosity and Number of Scattered Photons

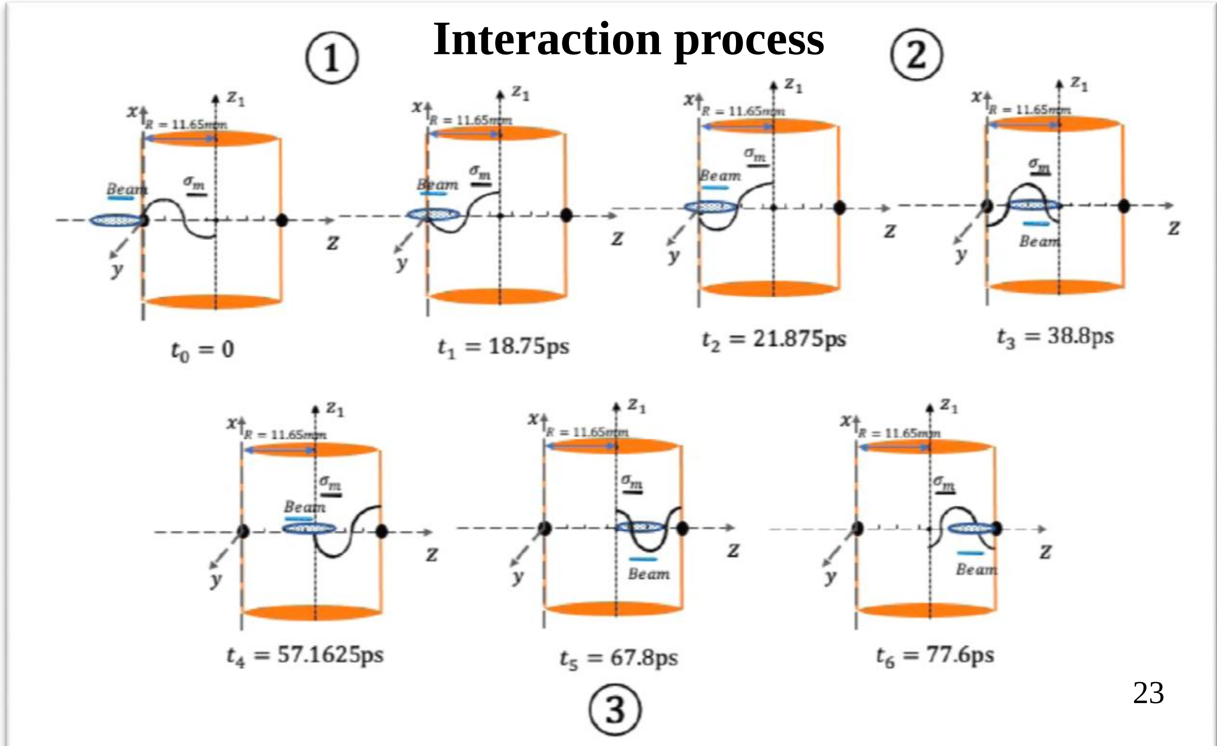
- The areal density of the photon number ($1/(m^2 \cdot s)$):

$$\overrightarrow{\sigma_m} = \frac{\vec{S}}{\omega_0} = \frac{1}{\eta\omega_0} E_m^2 J_0(K_c r_1) J_1(K_c r_1) \sin(\omega t)\cos(\omega t)\vec{r_1}$$

- The luminosity in the Compton scattering process : $B = 1, f' = 1$

$$L = N_2 \cdot 2Bf' \int \sigma_m(r_1) f_2(x_2, y_2, z_2, t) dxdydzdt \qquad f_2(x_2,y_2,z_2,t) = \frac{1}{2\pi\sigma_{x2}\sigma_{y2}\cdot\sqrt{2\pi}\sigma_{z2}} \exp\left[-\frac{1}{2}\left(\frac{x_2^2}{\sigma_{x2}^2} + \frac{y_2^2}{\sigma_{y2}^2} + \frac{z_2^2}{\sigma_{z2}^2}\right)\right]$$

- For ω'_{max}= 9 MeV, the luminosity of the three parts is $4.3 \times 10^{33}\ /m^2$, $5.14 \times 10^{33}\ /m^2$, $3.18 \times 10^{33}\ /m^2$.
- The number of the scattered photons in the three parts is 17193, 20541, 12725 respectively.

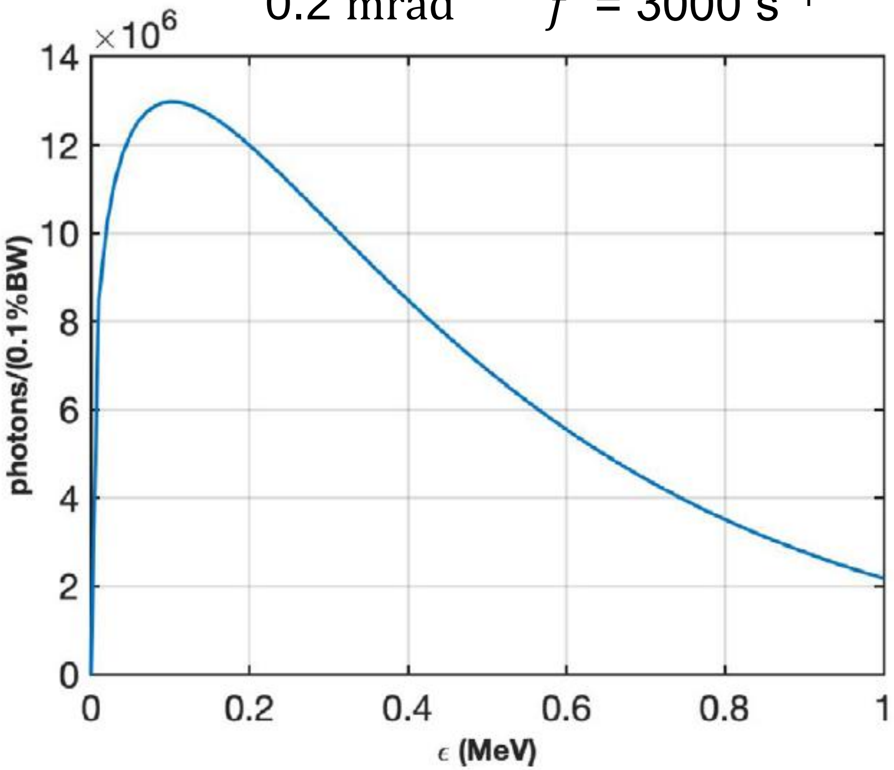


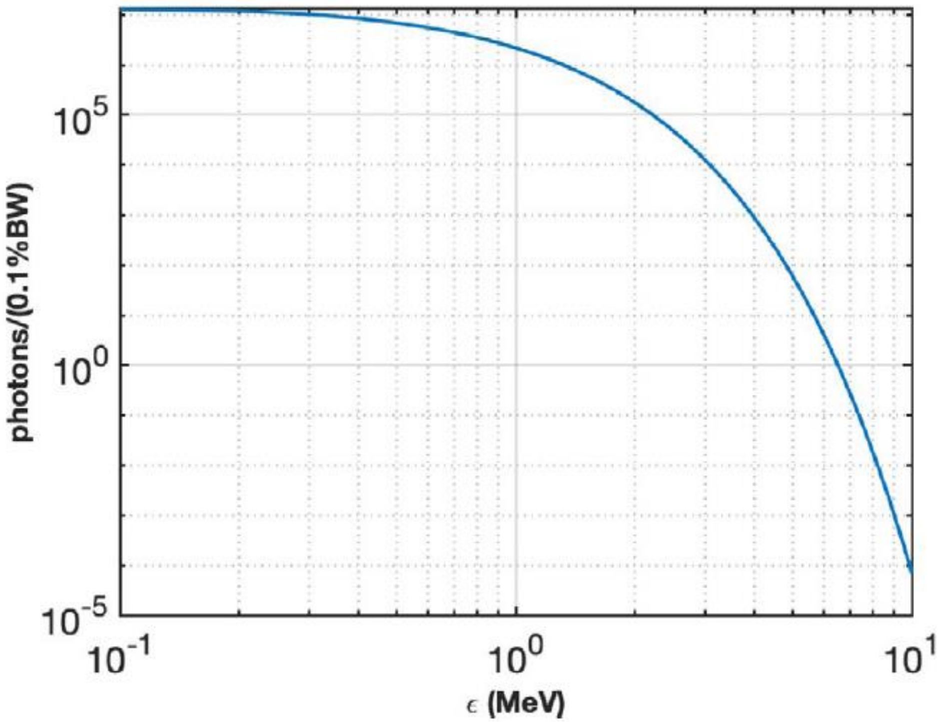
Synchrotron Radiation

The photon flux (photons/s/mrad /0.1%BW):

$$\frac{dF_{bm}(y)}{d\theta} = 2.457 \times 10^{13} E(\text{GeV}) I(A) G(y) \qquad G(y) = y\int_y^\infty K_{\frac{5}{3}}(y')dy'$$

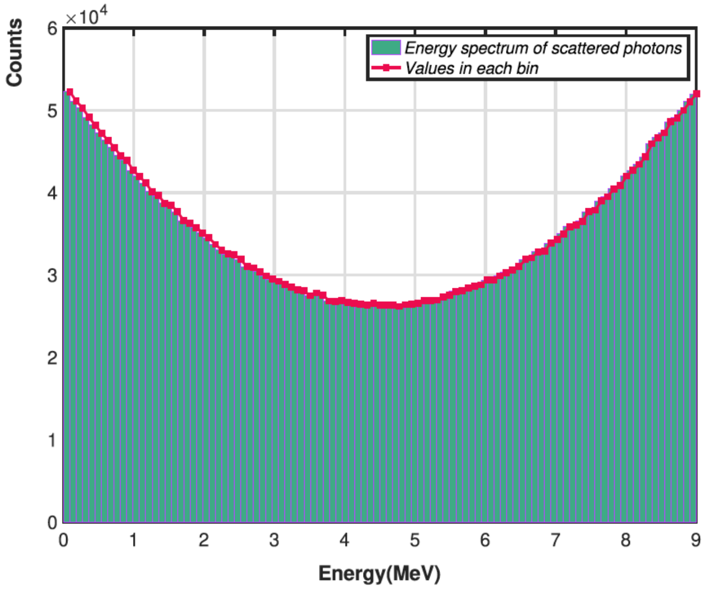
0.2 mrad $f' = 3000\ s^{-1}$



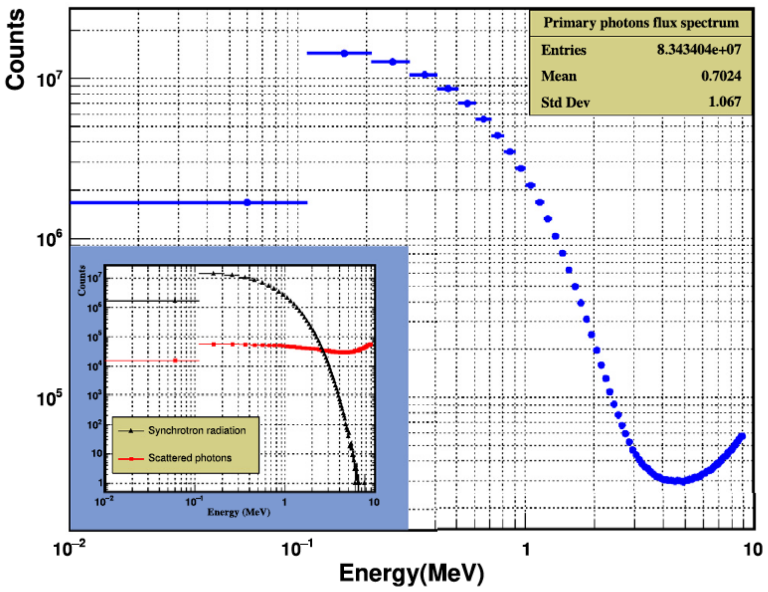


Monte-Carlo Simulation

- The energy spectrum of the scattered photons



- The scattered photons and the synchrotron radiation.



- Photons flux spectrum

400 cm polyethylene and 0.2 cm lead

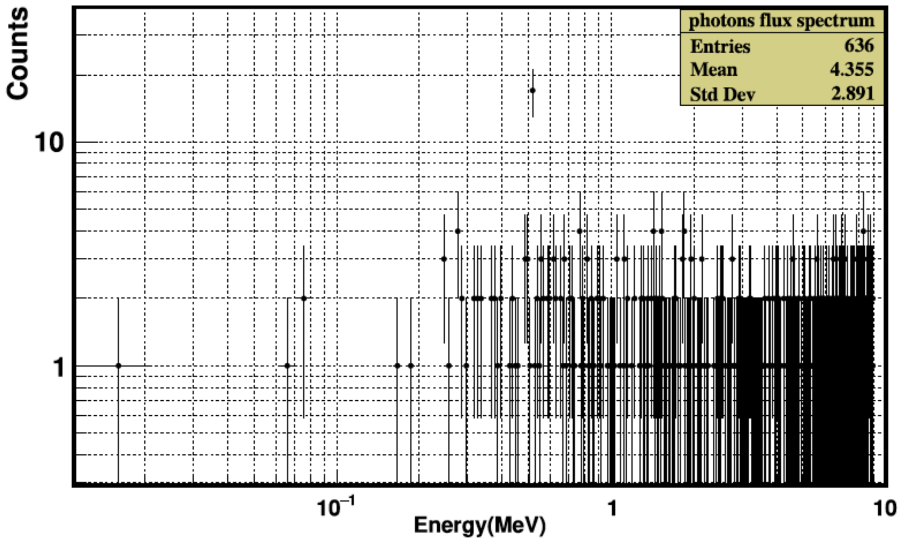


Table 2
The number of synchrotron radiation and scattered photons before and after shielding. B is the signal-to-noise ratio. After shielding, low-energy synchrotron radiation photons are absorbed.

Energy (0–9 MeV)	Before shielding	After shielding
Scattered photons(S)	3.519913×10^6	648
Synchrotron radiation(N)	7.991446×10^7	2
B(S/N)	0.44	324

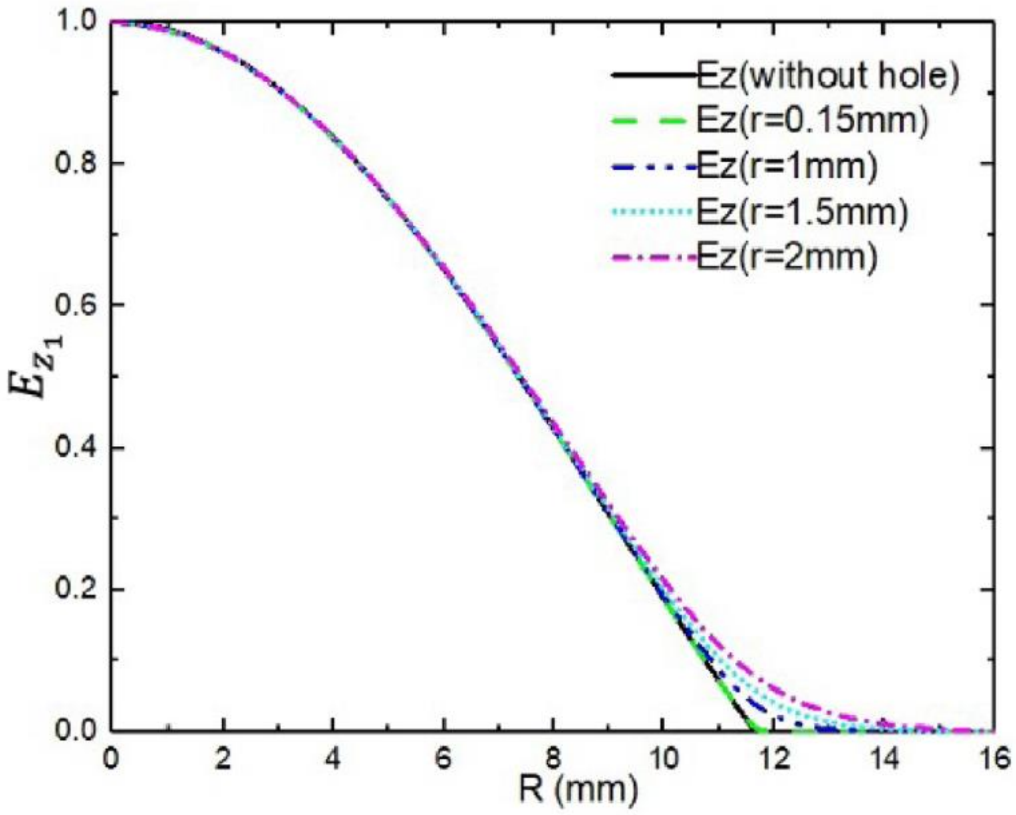
Effect of the Hole Radius

The resonance frequency and Q value of the cavity comes from the theoretical calculation, the CST simulations without holes and the CST simulations with the hole radius, 0.15 mm.

Parameter	Frequency (GHz)	Q value
Theoretical calculation	9.848975	11055.4
Simulation (without hole)	9.848976	11048.2
Simulation (hole radius 0.15 mm)	9.848973	11043.8

The variation of the resonance frequency in the cavity with the hole radius 1 mm, 1.5 mm, and 2 mm. The resonance frequency decreases slightly with the increase of the hole radius. The influence on the resonance frequency can be corrected by fine-tuning the cavity size.

Hole radius/mm	Frequency/GHz
1.0 mm	9.84790
1.5 mm	9.84533
2.0 mm	9.84026



- **Almost no effect on the field, the effect on the frequency can be compensated.**
- The energy storage in the cavity is 0.001J.

$$W = \frac{\varepsilon_0}{2} \cdot 2\pi l E_m^2 \int_0^R J_0^2(\frac{2.405}{R} r) r dr = \frac{1}{2} \pi \varepsilon_0 R^2 l E_m^2 J_1^2(2.4)$$

Possible Background

The effect of radiation in the field on the electron beam.

- In the TM_{010} mode:

$$E_{z_1} = E_m J_0(K_c r_1),$$

$$\bar{E}_{z_1} = \frac{\int_{-R}^{R} E_{z_1} dr_1}{2R}.$$

$$\bar{E}_{z_1} = 6.11351 \times 10^6 \ \mathrm{V/m}$$

- Electric Field:

$$E = \gamma m_0 c^2 = 120\mathrm{GeV}$$

$$F = q\bar{E}_{z_1} = \frac{\gamma m_0 c^2}{r}$$

$r = 19.629$ km; Bending radius

$$\epsilon_c = 2.218 \frac{E^3}{r} = 195.257 \ \mathrm{keV}$$ Critical energy

- Electric Field:

$$H_\varphi = -E_m \frac{1}{\eta} J_1(K_c r) \sin \omega t$$

$r = 28.837$ km; Bending radius

$$\epsilon_c = 2.218 \frac{E^3}{r} = 132.828 \ \mathrm{keV}$$ Critical energy

- Synchrotron Radiation: Bending radius: **10.7 km,** Critical energy: **352.8 keV.**

Error analysis

- The laser alignment accuracy is up to 5×10^{-7};
- The stability of the high-frequency microwave source itself can reach $10^{-5} \sim 10^{-6}$;
- Assuming the detector can reach the order of 10^{-4} under good calibration;
- The measurement accuracy of the beam energy can reach the **6MeV@120GeV** $(\boldsymbol{\Delta E/E \sim 5 \times 10^{-5}})$

Summary

Laser-Compton

- **1D fitting: 1MeV@120GeV, 0.6@80GeV， 0.3@40GeV**
- **2D fitting： 0.4 MeV@120GeV**

Microwave-Compton

- **6MeV@120GeV; <6MeV@80GeV;**
- **A simple method+ γSR beamline**

Center of Mass

- **Potential corrections of c.m. energy**
- **Beam energy uncertainties from surroundings**

Thanks

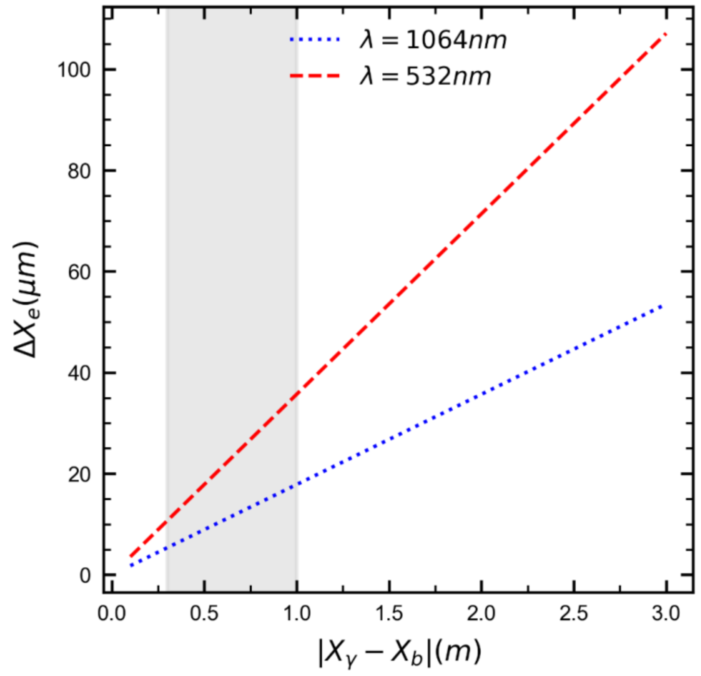
Backup

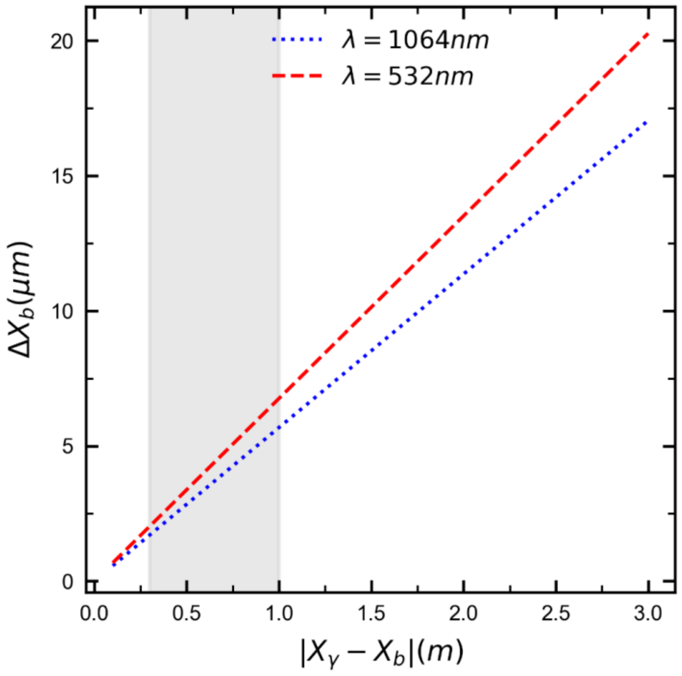
Requirement of measurement accuracy

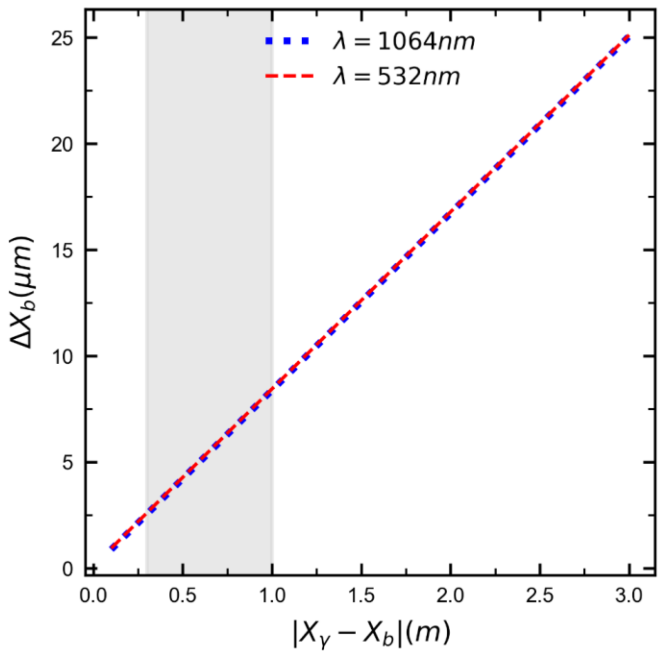
$1MeV$ ←

$$\frac{\Delta E_{beam}}{E_{beam}} = \sqrt{\left(\frac{\Delta X_{edge}}{|X_{edge} - X_{beam}|}\right)^2 + \left(\frac{|X_\gamma - X_{edge}|\Delta X_{beam}}{|X_{beam} - X_\gamma||X_{edge} - X_{beam}|}\right)^2 + \left(\frac{\Delta X_\gamma}{|X_{beam} - X_\gamma|}\right)^2}$$

- The requirement for the measurement of positions: ΔX_{edge}, ΔX_{beam}, ΔX_γ







Systematic deviation

- Considering the track of scattered electrons of different energies in dipole
- The deviation by the synchrotron radiation.

Source	Error of device	Systematic deviation in beam energy
Dipole (0.5T, 3m)	$\Delta B/B = 0.2\%$	$\Delta E = 9.75 \pm 0.04$ MeV
Position deviation by scattered electrons with different energies	$\frac{\Delta s}{s} = 4.8 \times 10^{-5}$	$\Delta E = 5.76$ MeV

- More systematic error sources need to be considered.
- Extrapolating the center-of-mass energy needs to be considered.