Beam Energy Measurement In Collider Experiments

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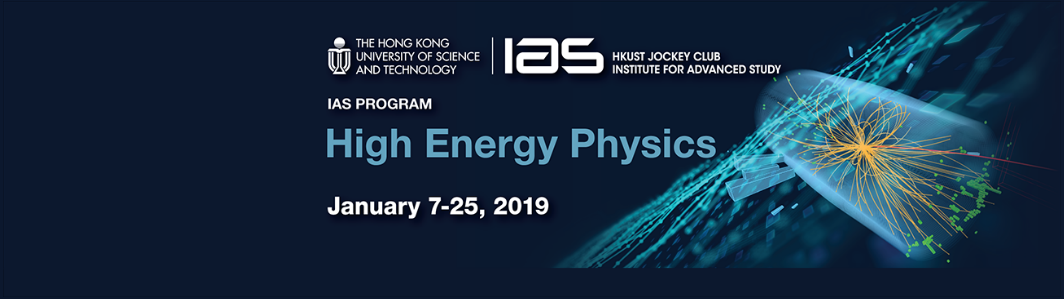
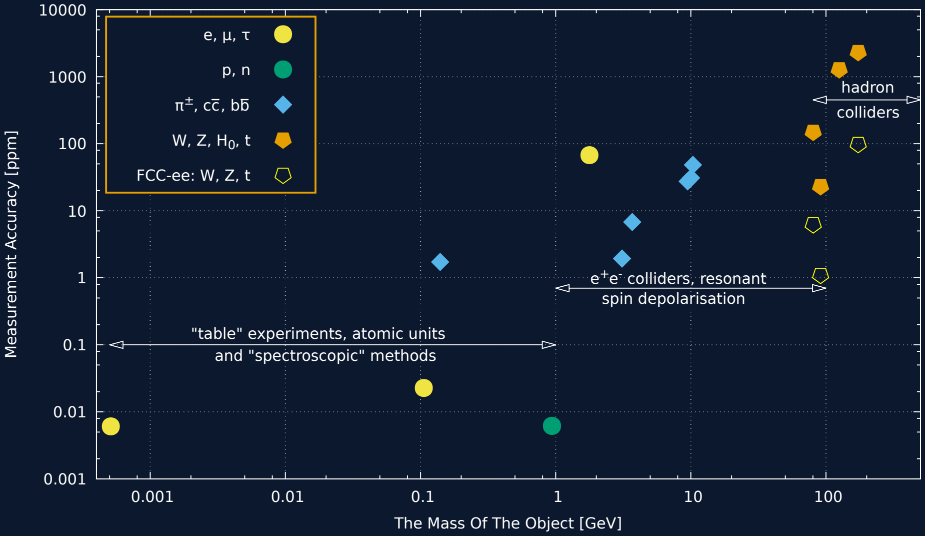


Who Weighs How Much

http://pdglive.lbl.gov



e^-e^+ colliders

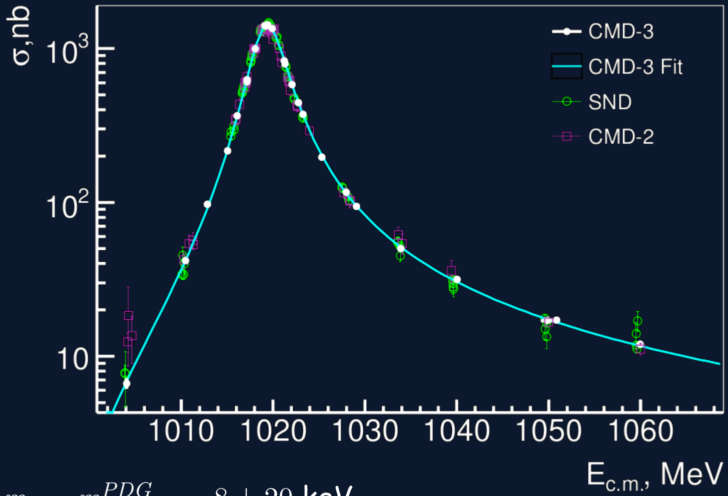
The CM energy in collision of electron with energy E_{e^-} and positron with energy E_{e^+} at crossing angle θ:

$$E_{\text{cm}} = \left[2E_{e^+}E_{e^-} + 2m^2 - 2\cos\theta\sqrt{E_{e^+}^2 - m^2}\sqrt{E_{e^-}^2 - m^2}\right]^{\frac{1}{2}}$$

Roughly, for collider with $\theta = \pi$ the average collision energy is:

$$\langle E_{\text{cm}}\rangle \simeq 2\sqrt{\langle E_{e^+}\rangle\langle E_{e^-}\rangle}$$

$e^+e^- \to K_S K_L$ at VEPP-2000 (2013)



CMD-3 Fit: $m_\phi - m_\phi^{PDG} = -8 \pm 20$ keV

Electron charge and Lorentz force

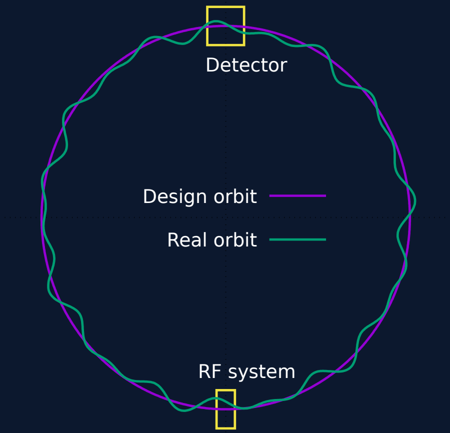
Consider electron beam with energy E and velocity $v = \beta/c$. In a field $B_\perp$ instant bent angle $d\alpha$ per arc length dl is

$$d\alpha = \frac{ec}{\beta}\frac{B_\perp}{E}\,dl$$

The closed orbit is defined by:

$$\int_0^{2\pi} d\alpha = 2\pi = \frac{ec}{\beta E}\int_0^L B_\perp(l)\,dl$$

Beam energy: $\beta E = \frac{ec}{2\pi}\int_0^L B_\perp(l)\,dl$



$$L = \beta c \cdot \frac{\text{harmonic number}}{\text{RF frequency}}$$

$\int B_\perp(l)\,dl$ accuracy by accelerator design parameters is $\simeq$0.1% or even worse.

Bargmann-Michel-Telegdi equation

Besides Lorentz force $B_\perp$ exerts a torque on the electron magnetic dipole moment and turns it in lab frame to the angle:

$$d\varphi = \frac{ec}{\beta}\frac{B_\perp}{E}\left(1+\gamma\frac{\mu'}{\mu_0}\right)dl \;=\left(1+\gamma\frac{\mu'}{\mu_0}\right)d\alpha\,, \qquad \text{where } \gamma = \frac{E}{mc^2}\,.$$

The ratio of the anomalous and normal parts of electron magnetic moment:

$$\frac{\mu'}{\mu_0} = \frac{g-2}{2} = 0.00115965218091 \pm 0.00000000000026$$

Electron $\overrightarrow{\text{spin}}$ rotation is $\left(1+\gamma\frac{\mu'}{\mu_0}\right)$ times faster than its own rotation.

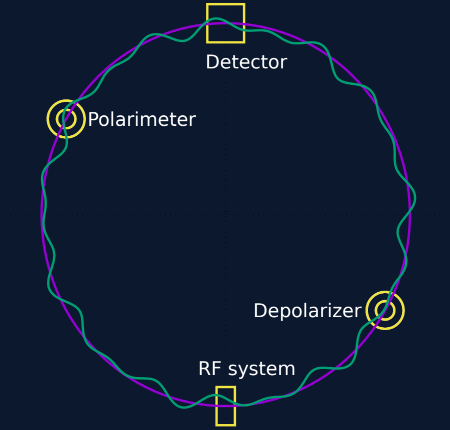
$B_\perp(l)$ does not affect $\dfrac{d\varphi}{d\alpha}$: this ratio only depends on electron γ-factor

RD - Resonant Depolarization

- Ω - spin precession frequency
- ω - beam revolution frequency

$$\frac{d\varphi}{d\alpha} = \frac{\Omega}{\omega} = 1 + \gamma\frac{\mu'}{\mu_0}$$

The Ω/ω ratio could be measured with accuracy better than 0.01 ppm.



RD approach requires:

- polarized beam,
- polarimeter & depolarizer.

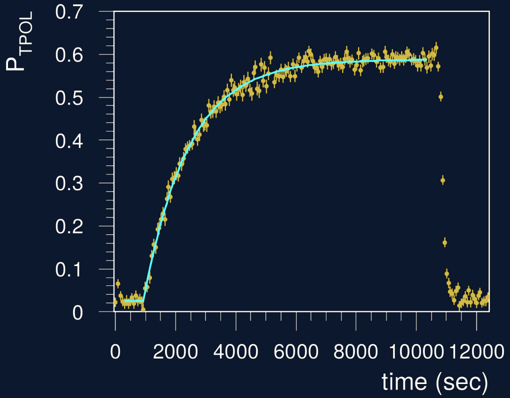
Accuracy limitations ($\Delta E_{cm}/E_{cm} \simeq$1 ppm):

- rare measurements - interpolation,
- non-flat orbit - $B_{||}$ affects Ω,
- E_{beam}(i.p.) $\neq \langle E_{beam} \rangle$,
- collision angle uncertainty, etc.

RD Examples

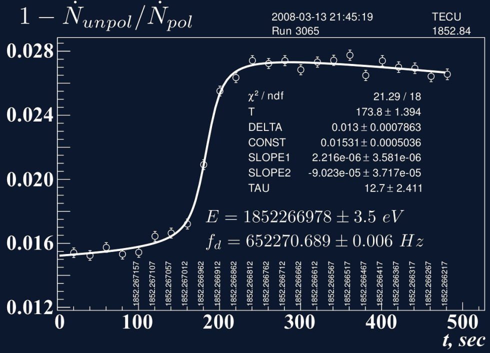
HERA electron beam (E=27.6 GeV) polarization build-up by the Sokolov-Ternov effect

26 June 2007



Slow e^- beam resonant depolarization at the VEPP-4M collider, E=1.852 GeV

13 March 2008



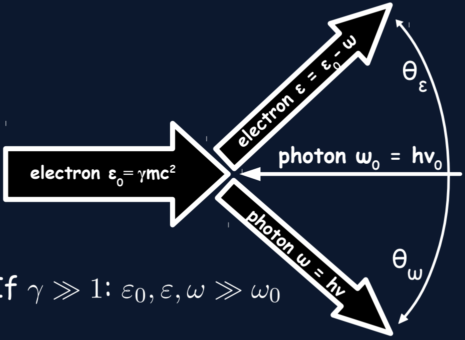
Excerpts from FCC-ee CDR

- Beam energy calibration by Resonant Depolarization is the basis for the precise measurements of the Z and W masses with a precision of $\sim$100 keV and $\sim$500 keV correspondingly.
- About 200 polarized pilot bunches/ring will not collide – just used for frequent beam energy measurements by RD.
- It is impossible to use RD at higher beam energies since the increased energy spread make the spin resonances too strong, reducing the asymptotic polarization to an unacceptably small value.
- E_{cm} near the $e^+e^- \to t\bar{t}$ threshold will be measured by the final state reconstruction of $e^+e^- \to W^+W^-, ZZ, Z\gamma$ events and from the knowledge of the W and Z masses.

Polarimeters on the Compton Effect

- Fast measurement of beam polarization is required for precise beam energy determination by RD.
- Positive experience at high beam energies – LEP, HERA, SLD.
- Known recipes: analyze scattered photons for transverse beam polarization, for longitudinal – use scattered electrons.
- Inverse Compton scattering is used for direct beam energy calibration at low-energy $e^{\pm}$ colliders: VEPP-4M, BEPC-II, VEPP-2000.
- Extend the latter experience for high energy colliders?

Inverse Compton Scattering



If $\gamma \gg 1$: $\varepsilon_0, \varepsilon, \omega \gg \omega_0$

Scattering parameter

$$u = \frac{\omega}{\varepsilon} = \frac{\theta_\varepsilon}{\theta_\omega} = \frac{\omega}{\varepsilon_0 - \omega} = \frac{\varepsilon_0 - \varepsilon}{\varepsilon}$$

is in the range

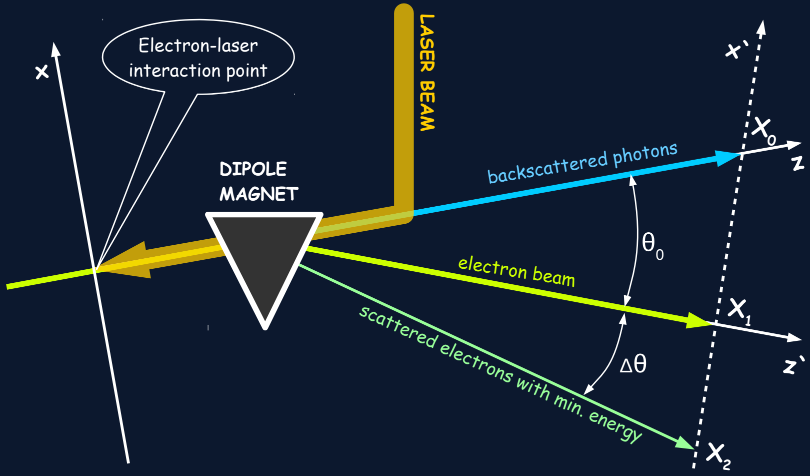
$$u \in [0, \kappa]\text{, where } \kappa = \frac{4\omega_0\varepsilon_0}{(mc^2)^2}$$

$\kappa \simeq 1.53$ if $\varepsilon_0 = 100$ GeV & $\omega_0 = 1$ eV

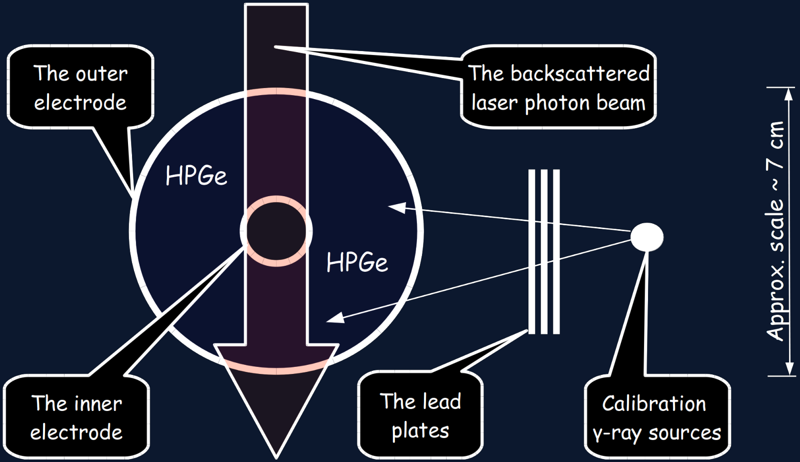
Scattering angles: $\theta_\omega = \frac{1}{\gamma}\sqrt{\frac{\kappa}{u} - 1}; \quad \theta_\varepsilon = \frac{u}{\gamma}\sqrt{\frac{\kappa}{u} - 1}.$

Note: $\max(\theta_\varepsilon) = 2\omega_0/mc^2$ (when $u = \kappa/2$). It is $\simeq 10$ μrad for green light.

Generic configuration: x-z plane

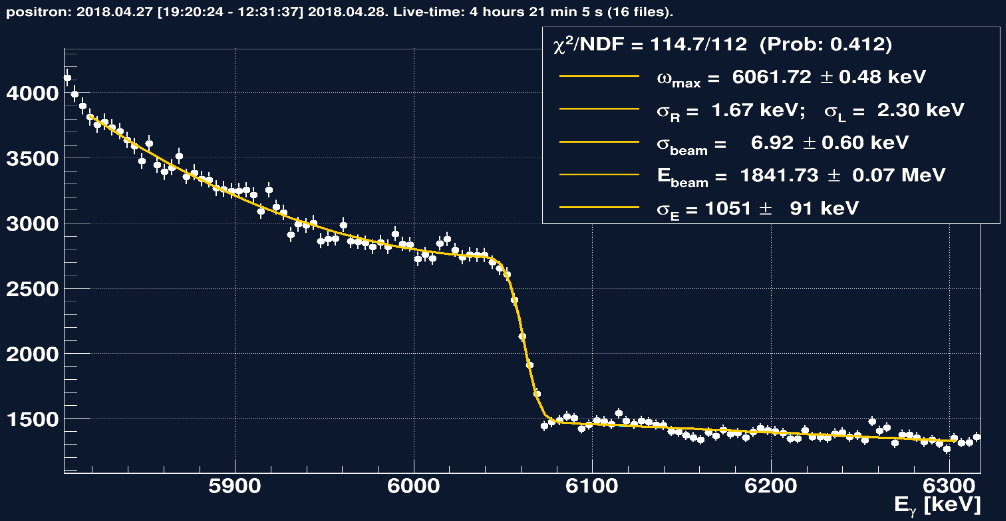


Beam Energy Calibration: Scattered γ-s



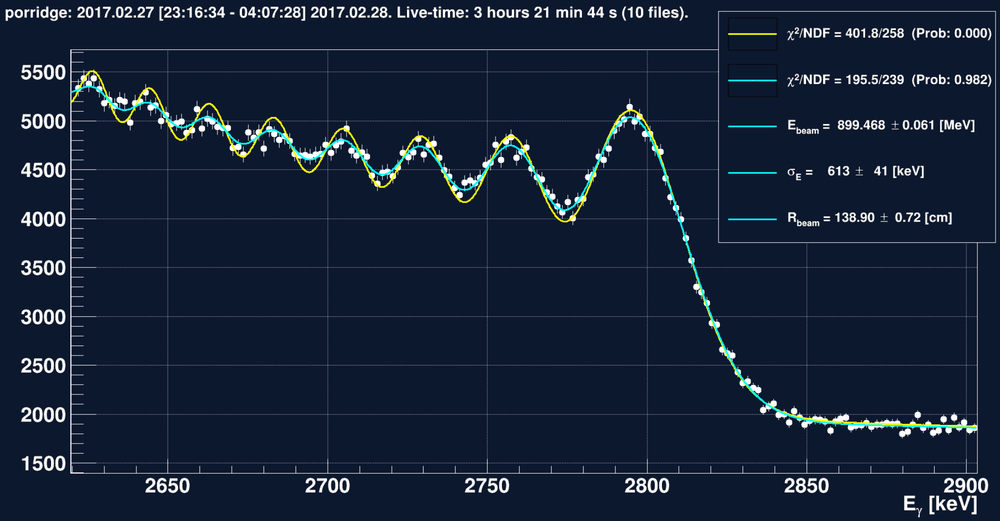
VEPP-4M (2005) ◦ BEPC-II (2010) ◦ VEPP-2000 (2012)

Compton γ-spectrum: BEPC-II



CO_2 laser ($\lambda_0 = 10.5910352\,\mu$m) backscattering in the BEPC-II straight section

Compton γ-spectrum: VEPP-2000



CO laser ($\lambda_0 = 5.426463\,\mu$m) backscattering in the VEPP-2000 bending dipole

Scattered electrons

The energy ε of scattered electron is:

$$\varepsilon = \frac{\varepsilon_0}{1+u} \to \min(\varepsilon) = \frac{\varepsilon_0}{1+\kappa}$$

Electron bending angle is defined by $B = ec\int B_\perp(l)\,dl$:

$$\theta_{\text{max}} \equiv \frac{B}{\min(\varepsilon)} = \frac{B}{\varepsilon_0} + \kappa\frac{B}{\varepsilon_0} = \frac{B}{\varepsilon_0} + \frac{4\omega_0 B}{(mc^2)^2} = \theta_0 + \Delta\theta$$

Maximum angles of scattered electrons:

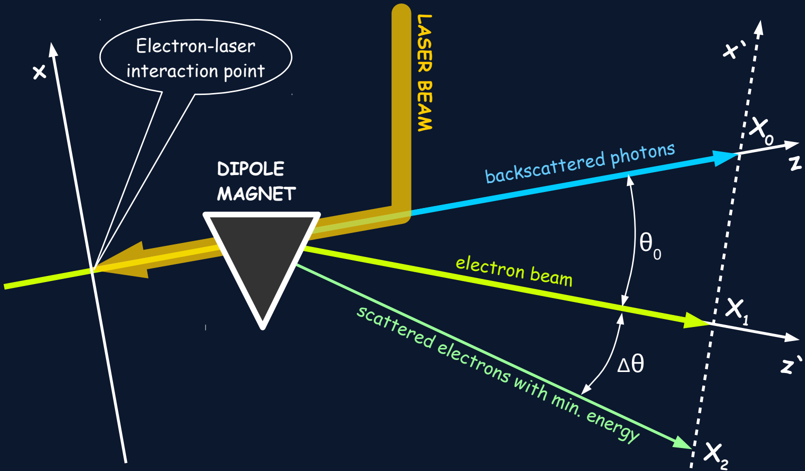
scattering: $\max(\theta_\varepsilon) = \dfrac{2\omega_0}{mc^2}$

bending: $\Delta\theta = \dfrac{2\omega_0}{mc^2}\cdot\dfrac{2B}{mc^2}$

Beam energy: $\gamma = \dfrac{mc^2}{4\omega_0}\cdot\dfrac{\Delta\theta}{\theta_0}$

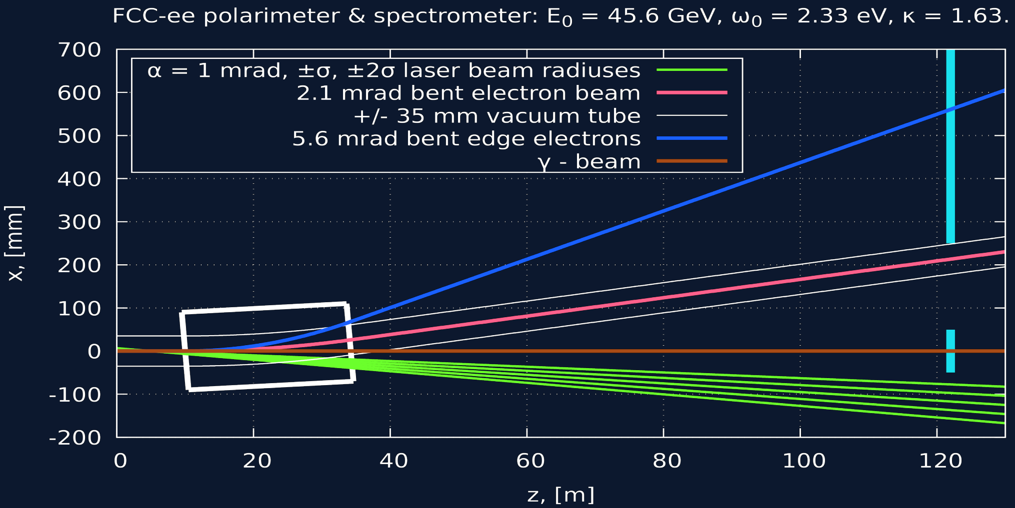
$\int B_\perp(l)\,dl$ IS NOT REQUIRED!

Generic configuration: x-z plane



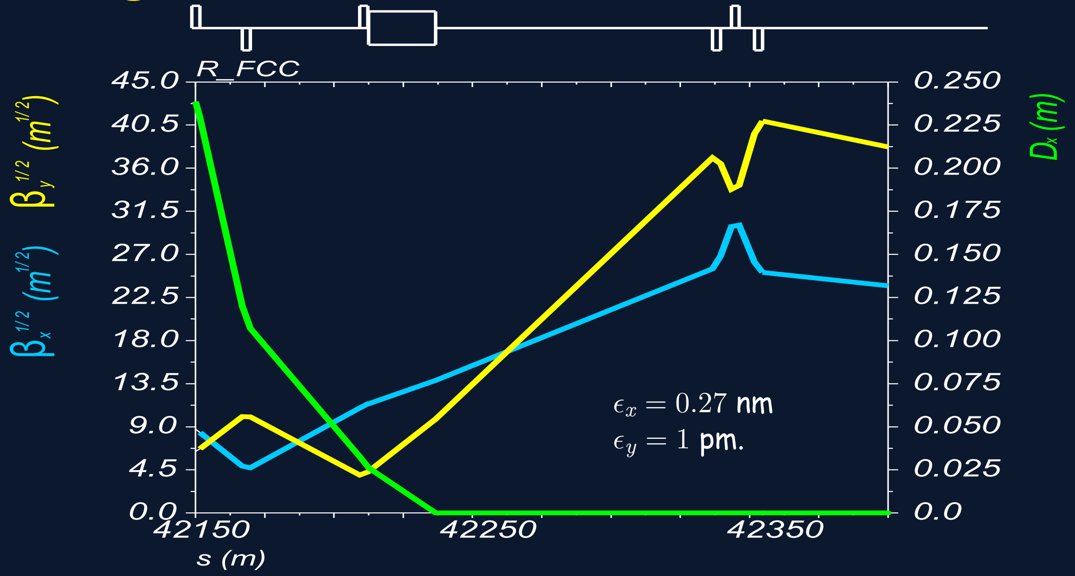
Since $\Delta\theta = \kappa\theta_0$ direct beam energy calibration is possible: $E = \frac{(mc^2)^2}{4\omega_0} \cdot \frac{\Delta\theta}{\theta_0}$

FCC-ee polarimeter: x-z plane

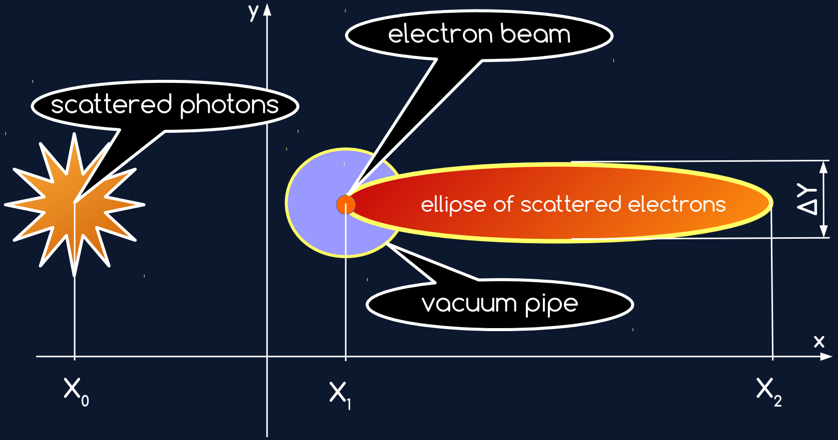


Blue bars – 2D silicon pixel detectors for scattered electrons & photons.

Integration to lattice (K. Oide, 2018)



The Polarimeter: x′-y′ plane



Direct beam energy measurement is: $E = \frac{(mc^2)^2}{4\omega_0} \cdot \frac{X_2 - X_1}{X_1 - X_0}$

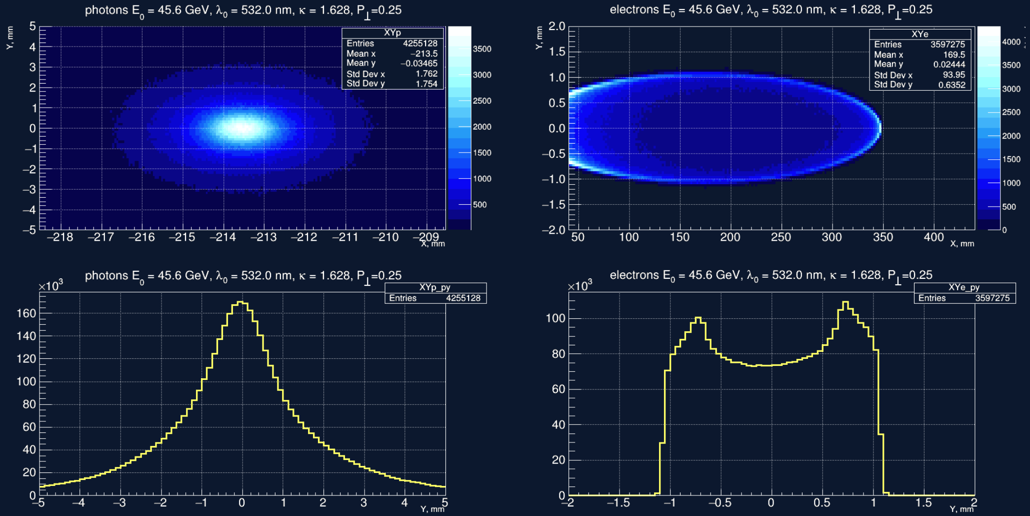
Si pixel detector for scattered electrons

- Detector size: L_x = 400 mm, L_y = 4 mm
- Number of pixels: N_x = 400, N_y = 80
- Pixel size: S_x = 1 mm, S_y = 50 μm

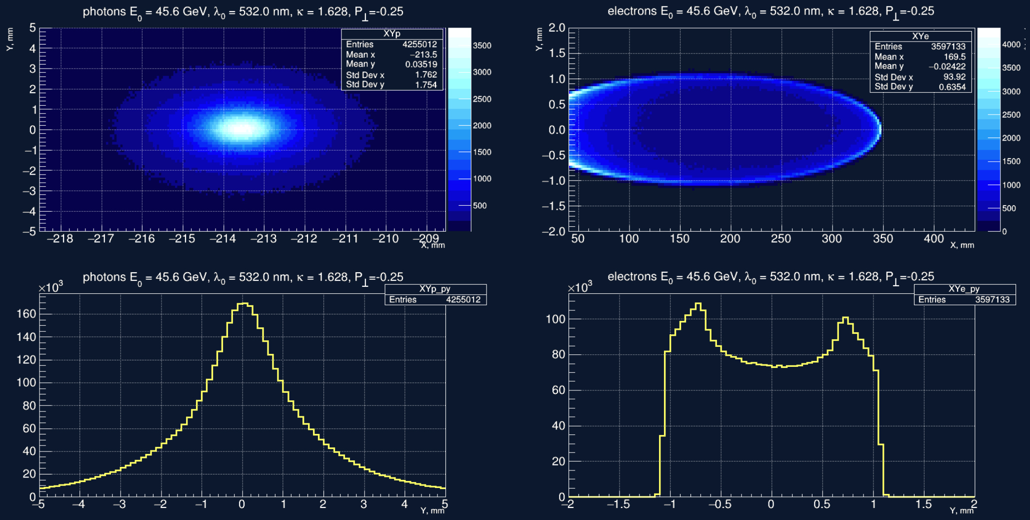
The similar setup have been studied in ILC note LC-M-2012-001:

"A Transverse Polarimeter for a Linear Collider of 250 GeV e Beam Energy"

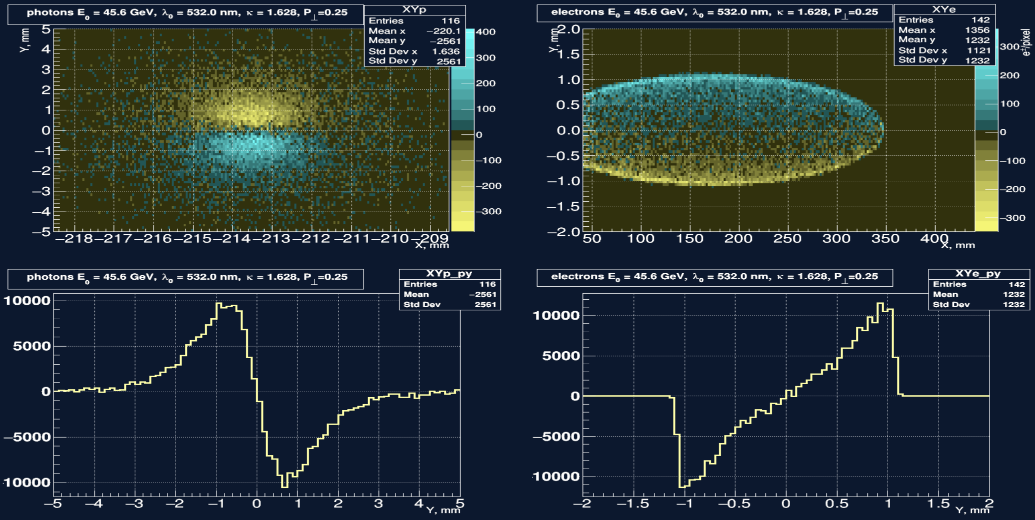
Scattered γ & e: $\xi_{\circlearrowright}\zeta_{\perp} = +0.25$



Scattered γ & e: $\xi_{\circlearrowright}\zeta_{\perp} = -0.25$



Scattered γ & e: The Difference



Polarimetry with electrons

- Maximum polarization asymmetry $d\sigma_\perp$ is observed at the angles

  $\theta_y^\gamma = \pm mc^2/E_{\text{beam}}$ for photons – doesn't depend on ω_0;

  $\theta_y^e = \pm 2\omega_0/mc^2$ for electrons – doesn't depend on E_{beam}.
- Scattered electrons propagate to the inner side of the beam orbit: there is no direct background from high energy SR photons.
- Electrons are ready to be detected by their ionization losses while γ's need to be converted to e^+e^- pairs: this leads either to low detection efficiency either to low spatial resolution.
- The flux density of electrons is much lower due to bending and corresponding spatial separation by energies. Simultaneous detection of multiple scattered electrons is thus much easier.
- Analysis of the scattered electrons distribution allows to measure the longitudinal beam polarization as well as the transverse one.

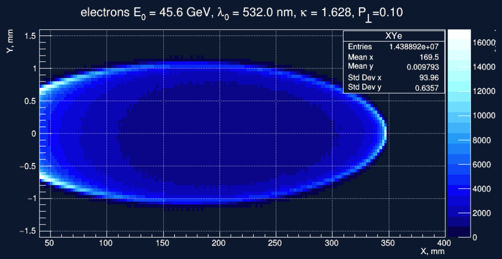
Compton Scattering cross section

for circular polarization of light $\xi_{\circlearrowright} = \pm 1$ depends on both longitudinal $\zeta_{\circlearrowright}$ and transverse $\zeta_{\perp}$ polarizations of the electron:

$$
\begin{aligned}
d\sigma_0 &= \frac{r_e^2}{\kappa^2(1+u)^3}\left(\kappa(1+(1+u)^2) - 4\frac{u}{\kappa}(1+u)(\kappa-u)\right) \quad du\, d\varphi,\\
d\sigma_{\parallel} &= \frac{\xi_{\circlearrowright}\zeta_{\circlearrowright} r_e^2}{\kappa^2(1+u)^3}\, u(u+2)(\kappa-2u) \quad du\, d\varphi,\\
d\sigma_{\perp} &= -\frac{\xi_{\circlearrowright}\zeta_{\perp} r_e^2}{\kappa^2(1+u)^3}\, 2u\sqrt{u(\kappa-u)}\cos(\varphi-\phi_{\perp}) \quad du\, d\varphi.
\end{aligned}
$$

For vertical electron (beam) polarization $\phi_{\perp} = \pi/2$

Fit: cross section & emittance



χ^2/NDF = 6356.7/6129 | Prob = 0.0208

X_0 = -213.538 ± 0.000 mm

X_1 = -000.008 ± 0.010 mm

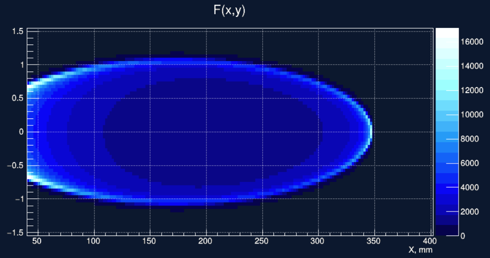
X_2 = 0347.631 ± 0.003 mm

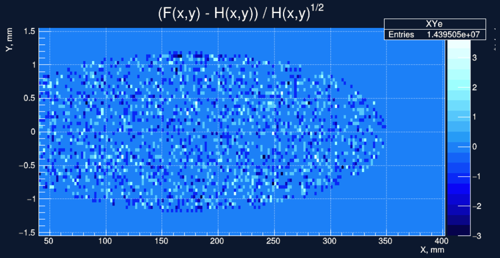
σ_x = 194.8 ± 4.4 μm

σ_y = 23.69 ± 0.02 μm

E_{beam} = 45.6032 ± 0.0035 GeV.

$P_\perp$ = 0.0997 ± 0.0016





Laser parameters

- λ_0 = 532 nm, waist σ_0 = 0.25 mm, z_R = 148 cm, divergence θ = 0.169 mrad.
- Interaction angle α = 1.0 mrad (horizontal crossing).
- Laser pulse: E_L = 1 mJ, τ_L=5 ns, f = 3 kHz, P_L = 80 kW, $\langle P_L \rangle$ = 3 W.
- Beam electron energy E_{beam} = 45.6 GeV, cross section $R_\times$ $\simeq$50%.
- Scattering probability $W = P_L/P_c \cdot R_\times \cdot \eta(R_L, R_A) \simeq 7 \cdot 10^{-8}$.
- $N_e = 10^{10}$ $e^{\pm}$/bunch: $\dot{N}_\gamma = f \cdot N_e \cdot W \simeq 2 \cdot 10^6$ s^{-1}.

Summary

- Detecting both scattered photons & electrons increases the reliability of beam polarization measurement.
- FCC-ee polarimeter provides $\simeq$ 1 % / s accuracy for $\zeta_\perp$.
- The beam energy spectrometer option does not require mandatory neither the B-field measurement nor the BPMs data:
  - statistical precision $\Delta E/E \simeq$ 100 ppm / 10 sec;
  - systematic effects estimation requires further studies: yet no limitations;
  - test of the approach does not require high beam energy and should be performed with low emittance beam at low energy.
- Polarimeter allows to measure beam sizes & positions.