IAS Program on High Energy Physics
Polarization Free Methods for Beam Energy Calibration

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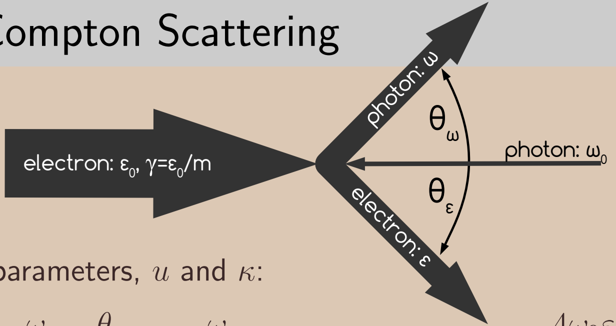
TALK OUTLINE

Introduction

- FCC-ee/CEPC aims to improve on electroweak precision measurements, with goals of 100 keV on the Z mass, and a fraction of MeV on the W mass.
- The resonant depolarization technique is the only known approach that showed the accuracy at the level of $\Delta E/E \simeq 10^{-6}$.
- My personal experience is based on beam energy measurement systems for VEPP-4M, BEPC-II and VEPP-2000 colliders. I will try to extend this approach for higher energies.

Inverse Compton Scattering



Scattering parameters, u and κ:

$$u = \frac{\omega}{\varepsilon} = \frac{\theta_\varepsilon}{\theta_\omega} = \frac{\omega}{\varepsilon_0 - \omega}; \quad u \in [0, \kappa]; \quad \kappa = \frac{4\omega_0 \varepsilon_0}{m^2}.$$

Scattering angles: $\theta_\omega = \frac{1}{\gamma}\sqrt{\frac{\kappa}{u} - 1}; \quad \theta_\varepsilon = \frac{4\omega_0}{m}\sqrt{\frac{u}{\kappa}\left(1 - \frac{u}{\kappa}\right)}.$

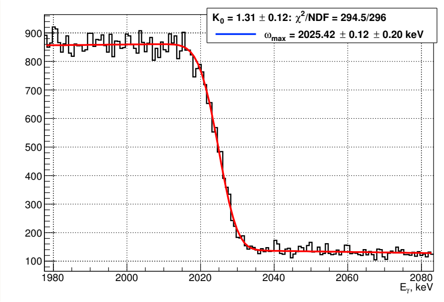
Maximum energy of scattered photon $(\theta_\omega = \theta_\varepsilon = 0)$: $\omega_{max} = \frac{\varepsilon_0 \kappa}{1 + \kappa}.$

$$\varepsilon_0 = \frac{\omega_{max}}{2}\left(1 + \sqrt{1 + m^2/\omega_0 \omega_{max}}\right) \simeq \frac{m}{2}\sqrt{\frac{\omega_{max}}{\omega_0}}.$$

Laser backscattering for beam energy calibration

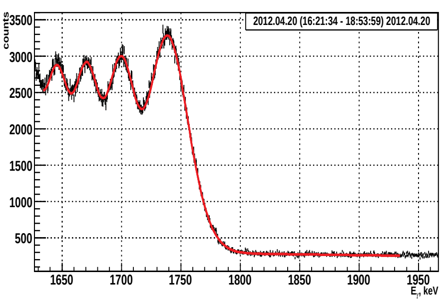
HISTORY: Taiwan Light Source^{1996}, BESSY-I,II^{1998,2002}, VEPP-3,4M,2000^{2008,2005,2012}, BEPC-II^{2010}, ANKA^{2015}

e. g. BEPC-II HPGe spectrum



$m_\tau = 1776.91 \pm 0.12^{+0.10}_{-0.13}$ MeV
Phys. Rev. D90 (2014) 012001

e. g. VEPP-2000 HPGe spectrum



Backscattering occurs inside the magnet: evident interference
Phys.Rev.Lett. 110(2013) 140402

Achieved accuracy is $\Delta E/E \simeq 3 \times 10^{-5}$ for $E < 2$ GeV

Accurate energy scale transfer: eV $\rightarrow$ MeV $\rightarrow$ GeV

- IR optics, 10P20 CO_2 laser line: $\omega_0 = 0.117065228$ eV
- γ-lines from excited nuclei as a good reference for ω_{max}:

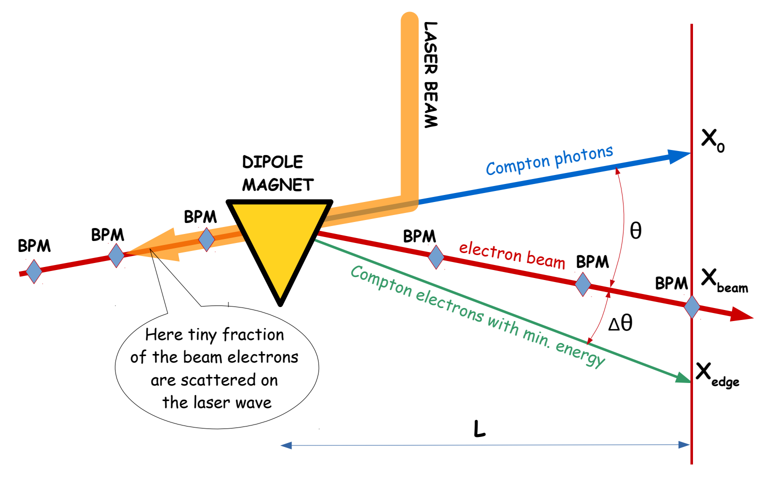
^{137}Cs	$\tau_{1/2} \simeq 30.07$ y	$E_\gamma = 0661.657 \pm 0.003$ keV
^{60}Co	$\tau_{1/2} \simeq 5.27$ y	$E_\gamma = 1173.228 \pm 0.003$ keV
		$E_\gamma = 1332.422 \pm 0.004$ keV
^{208}Tl	$\tau_{1/2} \simeq 3$ m	$E_\gamma = 2614.511 \pm 0.013$ keV
^{16}O*		$E_\gamma = 6129.266 \pm 0.054$ keV

- High energy physics scale[1]:

J/ψ	$3096.900 \pm 0.002 \pm 0.006$ MeV
$\psi(2S)$	$3686.099 \pm 0.004 \pm 0.009$ MeV

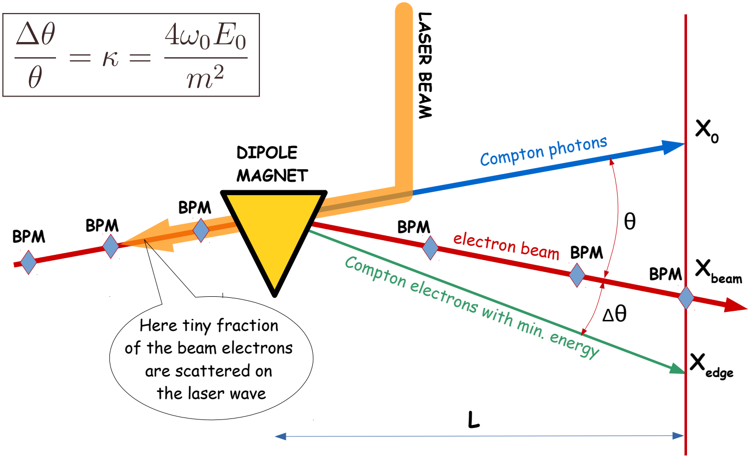
[1] Final analysis of KEDR data, Physics Letters B 749 (2015) 50-56

Spectrometer with laser calibration

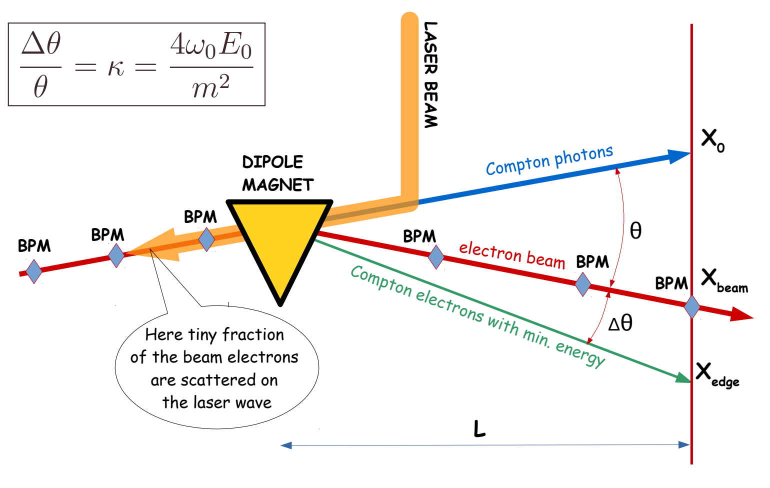


Spectrometer with laser calibration

$$\frac{\Delta\theta}{\theta} = \kappa = \frac{4\omega_0 E_0}{m^2}$$

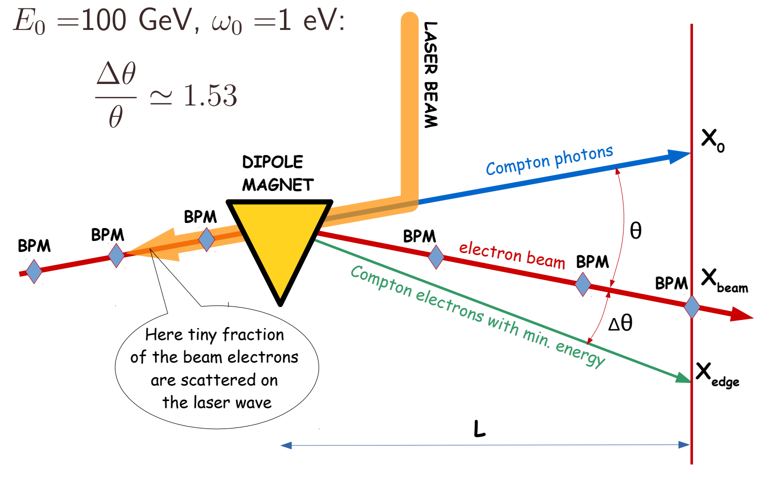


Spectrometer with laser calibration



Access to the beam energy: $E_0 = \dfrac{\Delta\theta}{\theta} \times \dfrac{m^2}{4\omega_0}$

Spectrometer with laser calibration



Access to the beam energy: $E_0 = \frac{\Delta\theta}{\theta} \times \frac{m^2}{4\omega_0}$

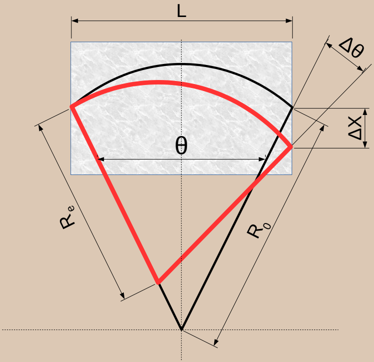
What do one has from $\Delta\theta$ measurement?

$$\boxed{\Delta\theta \frac{m^2}{4\omega_0} = \frac{1}{c}\int B dl}$$

- $\Delta\theta$ is a measure of a B-field integral along the trajectory which is *very close to the beam orbit* (see next slides).
- $\Delta\theta$ is independent of beam energy: fast energy changes may be detected by BPMs. I. e. increase of $\Delta\theta$ measurement time does not influence the beam energy measurement accuracy.

- Measurement of θ is outside of this talk. One can have a look at the experience of LEP spectrometer as well as ILC beam energy spectrometer studies.

Two arcs in a dipole of length L



Note that $\boxed{R_e = R_0/(1+\kappa).}$

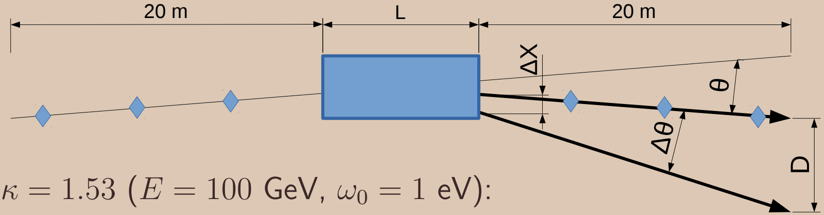
S_0, R_0 – black arc length & radius,
S_e, R_e – red arc length & radius. So

$$S_0 = 2R_0 \arcsin\left[\frac{L}{2R_0}\right] \text{ and}$$

$$S_e = 2R_e \arcsin\left[\frac{\sqrt{L^2+\Delta X^2}}{2R_e}\right],$$

where $\Delta X = \sqrt{R_e^2 - \left[\frac{LR_e}{2R_0}\right]^2} - \sqrt{R_e^2 - \left[L - \frac{LR_e}{2R_0}\right]^2}$.

Apparatus: general consideration



Let $\kappa = 1.53$ ($E = 100$ GeV, $\omega_0 = 1$ eV):

θ mrad	$\Delta\theta$ mrad	L m	ΔX mm	$\Delta S/S$	D mm
1	1.53	10	3.83	$2.59 \cdot 10^{-7}$	46
2	3.06	10	7.65	$1.04 \cdot 10^{-6}$	92
1	1.53	5	1.91	$2.59 \cdot 10^{-7}$	46
2	3.06	5	3.83	$1.04 \cdot 10^{-6}$	92

$\Delta S/S \propto \kappa\theta$ a)

$\Delta X \propto \kappa\theta \cdot L_{dipole}$ b)

$D \propto \kappa\theta \cdot L_{arm}$ c)

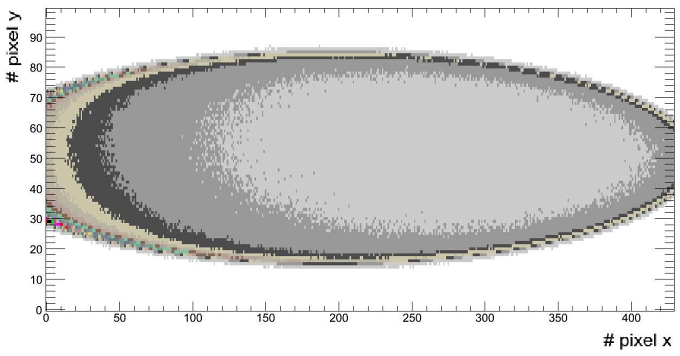
An ideal case: a) small angle; b) short dipole; c) long arm.

2D detector for scattered electrons?

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

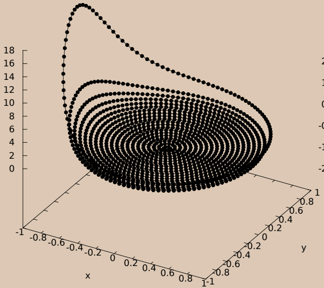
Itai Ben Mordechai and Gideon Alexander (LC-M-2012-001)

"... For the detection of the scattered electrons we consider only a position measurement using a Silicon pixel detector placed at a distance of 37.95 m from the Compton IP. The active dimension of the detector is 2×200 mm^2. The size of the pixels cell taken is 50×400 μm^2 similar to the one used in the ATLAS detector [9]. This scheme yields an approximate two dimensional resolution of 14.4×115.5 μm^2 [10] with a data read-out rate of ..."

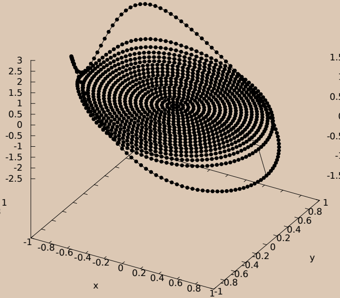


Scattering cross sections & e-beam polarisation.

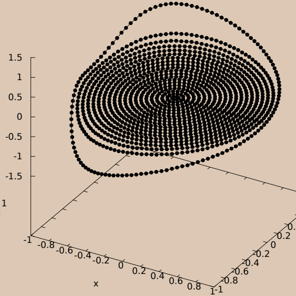
Unpolarised



Longitudinal

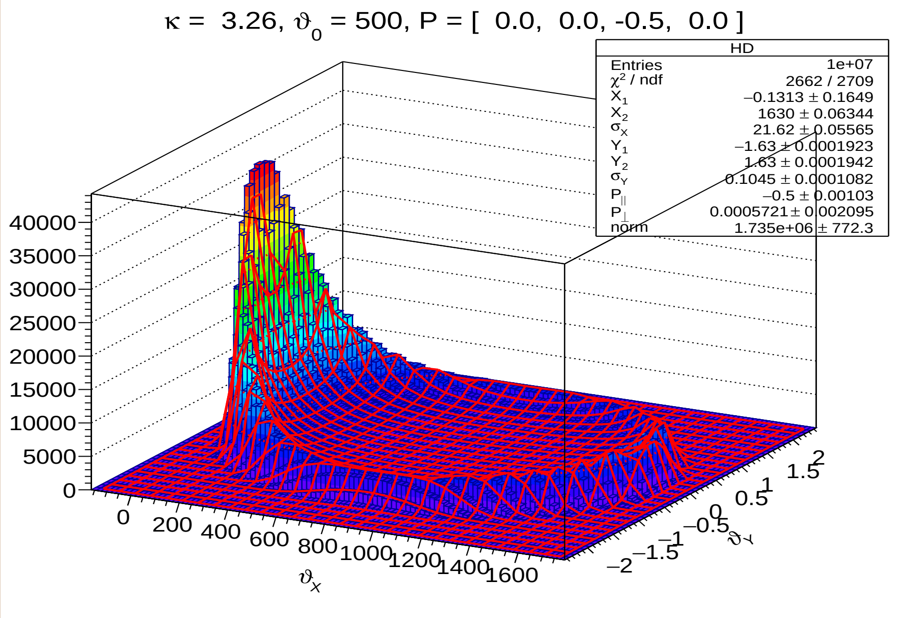


Transverse



In the plane of electron angles θ_x, θ_y
(after scattering and bending in a dipole)
cross section lies within the elliptical kinematic-bounded area.

200×100 pixels "detector". $\xi_{\circlearrowright}\zeta_{\parallel} = -0.5$



Fit results. $\xi_{\circlearrowright}\zeta_{\parallel} = -0.5$

X fit range is [200 : 1650]
200 horizontal bins means resolution $\sigma_X/X \simeq 0.005/\sqrt{12} = 0.14\%$

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FCN=2662.5 FROM MIGRAD STATUS=CONVERGED 257 CALLS 258 TOTAL
EDM=3.9346e-08 STRATEGY=1 ERROR MATRIX UNCERTAINTY 0.8 per cer
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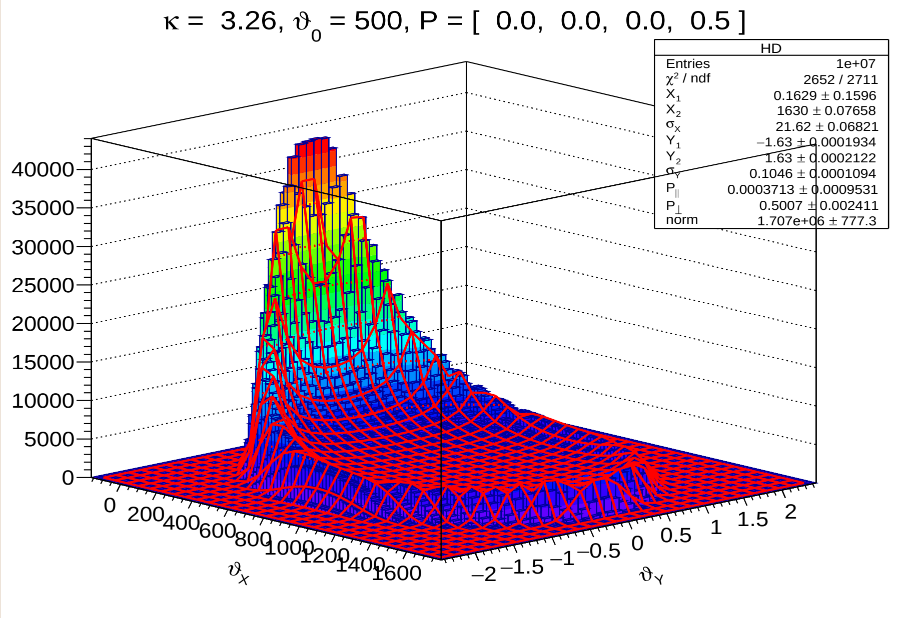
NO.	NAME	VALUE	ERROR	Remark
1	X_1	-1.3130e-01	1.64882e-01	$\Delta X_1/X_2 \simeq 1.0 \cdot 10^{-4}$
2	X_2	1.62998e+03	6.34381e-02	$\Delta X_2/X_2 \simeq 3.9 \cdot 10^{-5}$
3	σ_X	2.16201e+01	5.56481e-02	horizontal beam size
4	Y_1	-1.6298e+00	1.92272e-04	vertical axis
5	Y_2	1.62973e+00	1.94174e-04	vertical axis
6	σ_Y	1.04485e-01	1.08179e-04	vertical spread
7	$P_\parallel$	-5.0003e-01	1.02951e-03	$P_\parallel = -0.500 \pm 0.001$
8	$P_\perp$	5.72060e-04	2.09542e-03	$P_\perp = 0.000 \pm 0.002$
9	norm	1.73486e+06	7.72345e+02	

200×100 pixels "detector". $\xi_{\circlearrowright}\zeta_{\perp} = 0.5$



Fit results. $\xi_{\circlearrowright}\zeta_{\perp} = 0.5$

X fit range is [200 : 1650]
200 horizontal bins means $\sigma_X/X \simeq 0.005/\sqrt{12} = 0.14\%$

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FCN=2651.75 FROM MIGRAD STATUS=CONVERGED 258 CALLS 259 TOTAL
EDM=4.0963e-07 STRATEGY=1 ERROR MATRIX UNCERTAINTY 0.4 per cen
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NO.	NAME	VALUE	ERROR	Remark
1	X_1	1.62941e-01	1.59586e-01	$\Delta X_1/X_2 \simeq 1.0 \cdot 10^{-4}$
2	X_2	1.63002e+03	7.65815e-02	$\Delta X_2/X_2 \simeq 4.7 \cdot 10^{-5}$
3	σ_X	2.16220e+01	6.82096e-02	horizontal beam size
4	Y_1	-1.6298e+00	1.93423e-04	vertical axis
5	Y_2	1.63003e+00	2.12161e-04	vertical axis
6	σ_Y	1.04595e-01	1.09394e-04	vertical spread
7	$P_\parallel$	3.71312e-04	9.53123e-04	$P_\parallel = 0.000 \pm 0.001$
8	$P_\perp$	5.00724e-01	2.41133e-03	$P_\perp = 0.501 \pm 0.002$
9	norm	1.70728e+06	7.77293e+02	

Conclusion

1. High energy lepton colliders require beam polarisation at least for use of resonant depolarisation approach at “low” energies.
2. With a 2D detector for scattered electrons both spin polarisation degree and direction could be measured with high accuracy.
3. Beam energy spectrometer was used at LEP and a lot of studies were made for ILC. No doubt it should be implemented on HF.

- A novel way for B-field integral measurements along the beam orbit is suggested with accuracy in the range of 1 – 100 ppm.
- With no additional equipment (except required for items 1,2,3) the accuracy of beam energy determination is limited by the accuracy of bending angle measurement (10 – 100 ppm) .
- Further studies require detailed simulations with realistic machine and scattered electrons detector parameters.

The end

THANK YOU!

Special thanks to the conference organizers for the invitation and warm welcome!