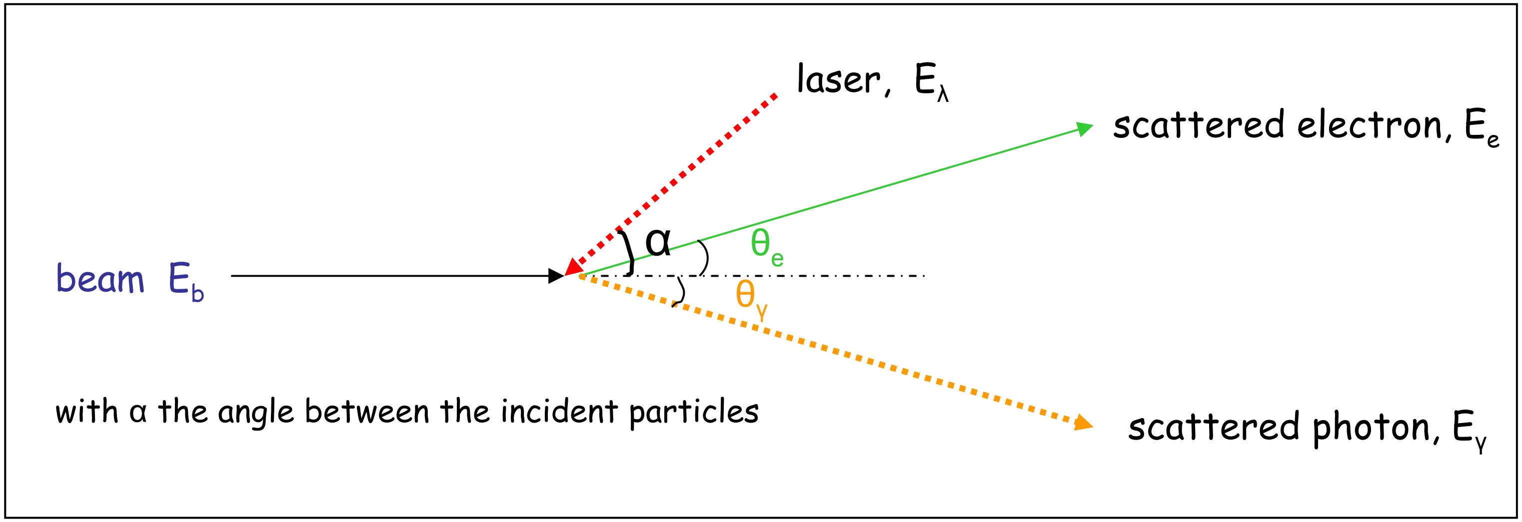
Precise Beam Energy Measurement using Compton back-scattering at the ILC

Process : $e_b + \gamma_L \rightarrow e' + \gamma'$

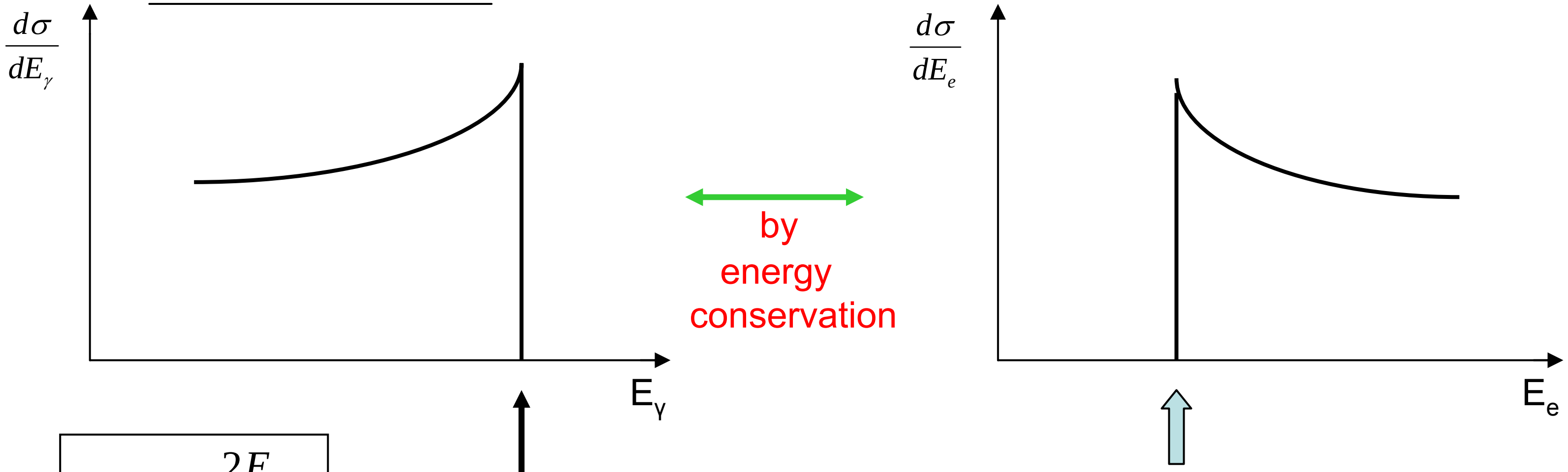


with α the angle between the incident particles

Basic properties (kinematics) of scattered photon resp. electron:

- ***sharp edge*** in the energy distribution
- both particles are ***strongly forward collimated***
- the ***position of the edge is not dependent on the initial polarization state***

in the lab frame



by energy conservation

$$\boxed{E_\gamma^{\max} = \frac{2E_b}{2 + \frac{1}{k_i}}}$$

with $k_i = 2\gamma E_\lambda / m_e$

$\gamma = E_b / m_e$

varies with the beam energy, E_b

$$\boxed{\Delta E_e < \Delta E_b}$$

The ***energy of the edge electrons*** depends

- on the primary ***beam energy*** (E_b = 250 GeV (45 … 500 GeV)
- the laser wavelength resp. the ***laser energy, E_λ*** (~ eV)
- the ***angle α***, the angle between the incoming particles (which should be chosen to be very small)

These quantities determine whether the edge electrons (photons) have a large or small energy; once E_λ and α are fixed ➔ access to the beam energy E_b

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Our basic requirement of ***$\Delta E_b/E_b = 10^{-4}$*** means an absolute shift of the beam energy of ***ΔE_b=25 (50) MeV at E_b=250 (500) GeV***

!

Example: E_b = 250 GeV, α = 0., CO_2 laser (E_λ=0.117 eV)

➔ ***E_e(edge) = 173 GeV and ΔE_e = 11.9 MeV***

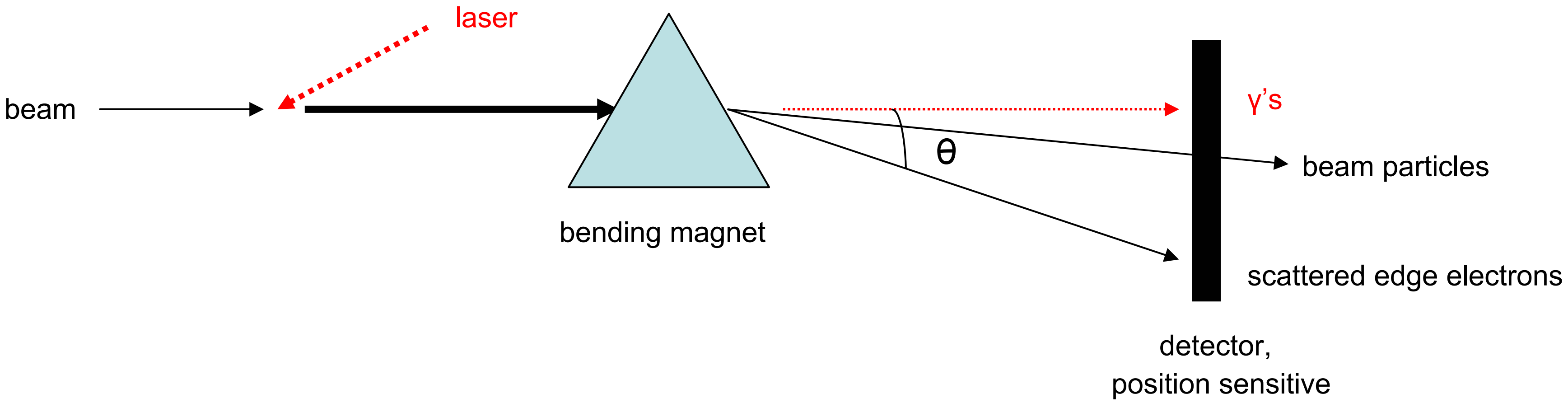
Nd:YAG (green, E_λ=2.33 eV)

➔ ***E_e(edge) = 25 GeV and ΔE_e = 0.254 MeV***

lasers with large wavelength are preferred

Sketch of a possible experiment

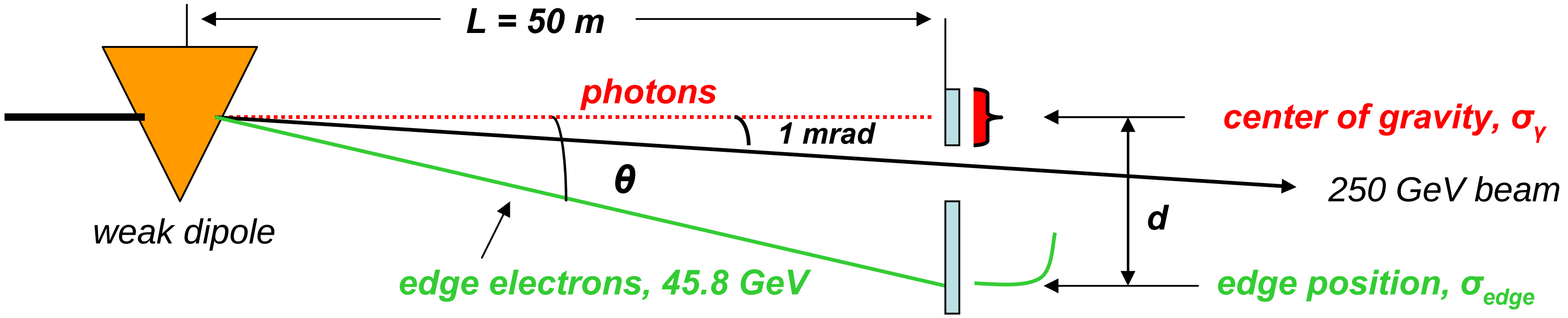
The beam electrons interact with the laser photons at very small angle α, so that downstream of the IP untouched beam particles (most of them), scattered electrons and photons exist. All these particles are strongly collimated in the forward direction.
By a dipole magnet these particles are divided into through-going photons, less deflected beam particles and scattered electrons with some larger bending angles.
The electrons with the largest bending angle are the edge electrons and they should be carefully measured.



Having precise information on the bending angle θ of the edge electrons and the B-field integral, the beam energy (for each bunch ?) can be determined -- ***how well ?***

Example: Aim: $\Delta E_b/E_b = 10^{-4}$

infrared Nd:YAG laser (E_λ = 1.165 eV)



in this example, Θ is 5.46 mrad
resulting to d = 27.3 cm

Note, if E_b changes by 25 MeV,

and ΔL = 0.1 mm, $\Delta B/B = 10^{-5}$ (with $B=\int B dl$)

one needs a precision for the distance **d** of

→ ***Δd = 5 μm !***

to recognize such a shift

Using a CO_2 laser with $E_\Lambda = 0.117$ eV and the same set-up

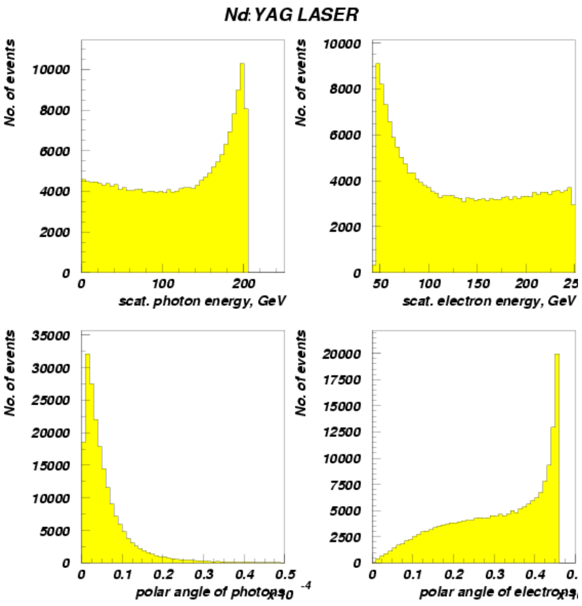
- energy of the edge electrons 172.6 GeV
  with an offset in the detector d = 7.2 cm

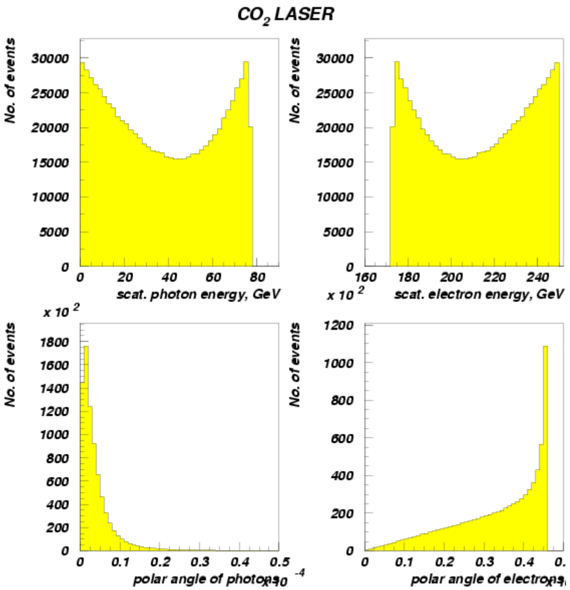
➔ ***Δd = 7-8 μm***

First GEANT simulations started including

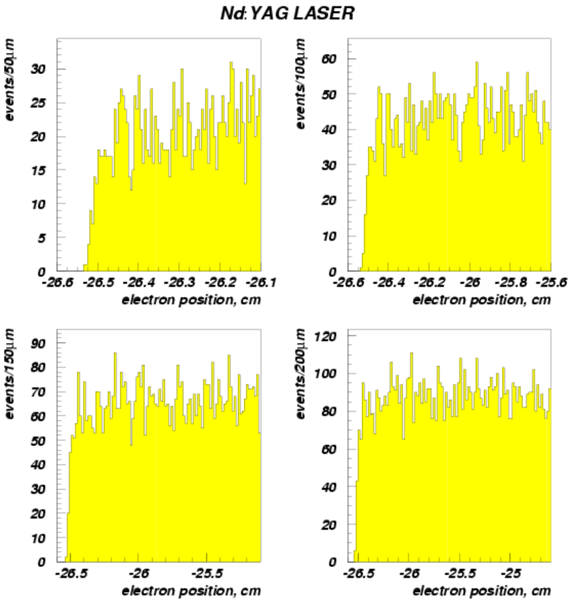
- beam sizes of the electron bunches (σ_x = 20 μm, σ_y = 2 μm, σ_z = 300 μm)
- beam energy spread of 0.15 % of the nominal energy,
- # of electrons/bunch = $2\ 10^{10}$, unpolarized
- bending magnet of 3 m length with B-field of 2.75 kG; fringe field included
- synchrotron radiation on
- distance between magnet and detector L = 50 m
- scattering angle in the initial state α = 8 mrad; vertical beam crossing
- infrared Nd:YAG laser (E_Λ = 1.165 eV) resp. CO_2 laser (E_Λ = 0.117 eV) used
- Nd:YAG laser: spot size at IP of 45 μm, power/pulse = 1 mJ
  and a pulse lenght of 10 psec (with a spacing of 337 nsec)
- CO_2 laser: spot size at IP of 100 μm, power/pulse = 1 mJ
  and a pulse lenght of 10 psec (with a spacing of 337 nsec)
- perfect overlap of both beams

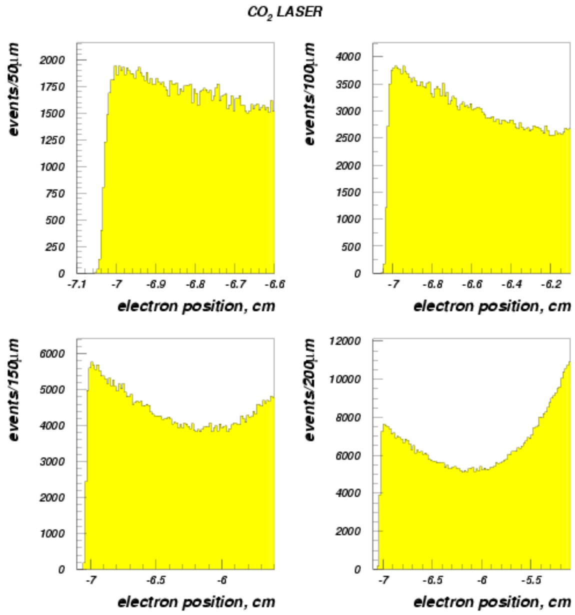
Characteristics of scattered particles:


Nd:YAG LASER

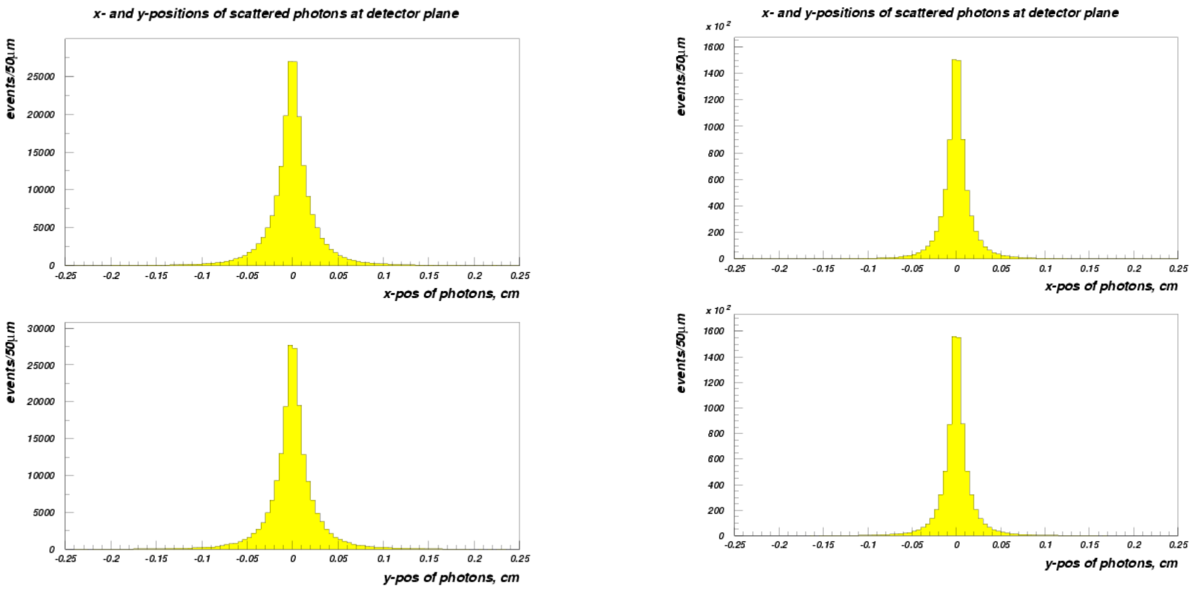

CO$_2$ LASER

Position of the edge electrons in the detector


Nd:YAG LASER


CO$_2$ LASER

Detector positions of the scattered photons



Clear, the CO_2 laser provides more electrons close to the edge than the Nd:YAG laser

due to larger cross section and somewhat better kinematics in the edge region.

With assumed laser and electron beam parameters and scattering angle a

→ # of Compton scatters $2\ 10^5$ for the Nd:YAG laser, while $8\ 10^5$ for the CO_2 laser

negligible event rate w.r.t. the total bunch intensity → method is nondestructive,

and the large bunch spacing should allow for single bunch measurements (?)

Summary (based on the example)

- Laser: ongoing laser activities

  - Nd:YAG laser (infrared)
    e.g. at TTF Nd:YLF laser (λ = 1.047 μm) → 3 MHz repetition rate
    and peak/power of 140 μJ
    → a factor 8-10 off our needs
  - CO_2 laser
    polarized positron source collaboration (NIM A 500 (2003) 232)
    proposed a CO_2 laser with 121 pulses with 2.8 nsec spacing
    and a pulse power of 250 mJ

    resp. recent Snowmass proposal (physics/0509016)
    → 3.6 10^4 pulses with 3 psec rms bunch duration and power/pulse of 2.1 mJ

  → CO_2 laser advantageous, but does not exist
  → infrared Nd:YAG (Nd:YLF) promising, power increase needed no showstopper

- Magnet:

  - a field error of 2 10^{-5} today achievable → very close to our needs (1-1.5) 10^{-5}
  - vertical bending preferred since $\sigma y \ll \sigma x$ (flat beam), also background smaller (?)

- Detector for scattered photons, electrons

  - measure the distance d with a precision of 5-8 μm, bunch by bunch (?) → CHALLENGING

- device also usable for (crude) beam profile determination, using the photon spatial distributions in the detector

With some optimism and further suggestions to improve the set-up

it seems possible to achieve $\Delta E_b/E_b = 10^{-4}$

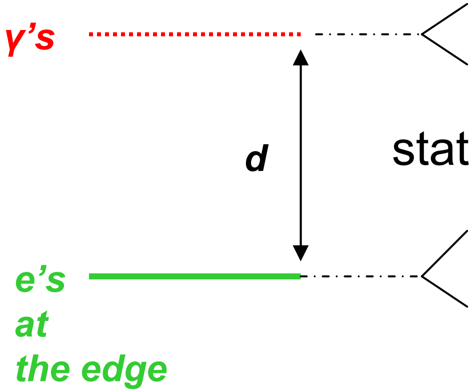
by Compton back-scattering of laser light

The idea to use Compton back-scattering for beam energy determination
has been refreshed in discussions with Amour Margaryan during a visit
of Yerevan in autumn 2004

$$\frac{\Delta E_b}{E_b} = \sqrt{\left(\frac{\Delta B}{B}\right)^2 + \left(\frac{\Delta \theta}{\theta}\right)^2}$$

$$\frac{\Delta \theta}{\theta} = \sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta d}{d}\right)^2}$$

Assume



γ's

$\sigma_\gamma = 5\ \mu m$ *(for centre of gravity)*

d

statistics ! **?** ➔ $\boxed{\Delta d/d = 3.3\ 10^{-4}}$

i.e. a factor 8.5 off (3.9 10^{-5} !)

e's at the edge

$\sigma_{edge} = 10\ \mu m$

Possible way out: 5 μm → 3 μm and 10 μm → 5 μm

➔ $\Delta d/d = 1.7\ 10^{-4}$

or increase L to 30 m ➔ $\Delta d/d = 2.2\ 10^{-4}$

or do both ➔ $\Delta d/d = 1.1\ 10^{-4}$

i.e. we are a factor 2.6 off

With some optimism and further ideas/suggestions to improve the set-up it seems possible to achieve $\Delta E_b/E_b = 5\ 10^{-5}$

The task may be divided into three steps:

Step No. 1

Fix the kinematics and understand the Compton scattering cross section w.r.t.

- the angle α, the laser wavelength, the laser polarization for
  - a) unpolarized beam electrons at E_b = 250 GeV (46 (Z pole), 500 GeV)
  - b) polarized beam electrons (longitudinal and transverse pol.)
- include the luminosity to estimate the rate of the Compton process in a detector

➔ optimize the event rate

Step No. 2

Based on the results from Step No.1, design an experimental layout for precise beam energy measurement, for each bunch crossing

Step No. 3

Try to have a first simulation of the experiment with GEANT