# Absolute Beam Energy Measurement in SuperKEKB using Inverse Compton Scattering

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**Abstract**

Absolute beam energy measurement in storage-ring colliders is challenging. Energy measurement based on inverse Compton scattering of a laser beam off the electron (or positron-) beam has been demonstrated to give very accurate, absolute beam-energy measurements on a number of machines up to the few-GeV energy range. In the following we explore the possibility of using this method at SuperKEKB. It appears an absolute accuracy of the energy measurement of 180 keV for the LER beam is achievable using a 10-W cw $CO_2$ laser and an HPGe detector, both available commercially. The same setup would give an accuracy of about 260 keV for the HER.

## 1 Motivation

With the unprecedented precision of SuperKEKB based on extremely high statistics the need of more accurate energy calibration becomes more pressing than at PEP-II and KEKB. In the absence of dedicted energy measurement, and with polarization measurements impossible, PEP-II relied on using the Υ(3S) resonant state to both pin down the cm energy as well as get an idea of the energy spread in the cm. As scaling ring energy down-and-up was needed to reach the Υ(3S), accuracy of this method was limited to several MeV at best.[1] Certain differences to the beam energy derived from magnet setting were difficult to resolve. A beam energy measurement accurate to better than an MeV, and the ability to also measure the beam energy spread, would have been of enormous benefit.

(probably need more here)

In addition, accurate knowledge of the beam energy and energy spread can be of significant help in understanding and tuning the machine. E.g. when adjusting the damping partitions, knowing exactly how the energy spread changes

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allows homing in on the desired setting in a minimum amount of time. Measuring the energy spread can allow an accurate measurement of momentum compaction $\alpha_p$ and can aid in monitoring the dispersion function. With a revolution time of 10$\mu$s, a sufficiently fast system might be gated to provide limited information of energy *vs* position in a bunch train.

# 2 Inverse Compton Scattering

The inverse Compton scattering process (scattering photons off energetic electons thereby transferring energy to the photon) is well understood and documented[2]. We only cite the salient point here.

## 2.1 Kinematics

Scattering photons off an electron or positron beam, the photons will gain energy depending on the incident angle between photon and electron beam of up to

$$E_\gamma = E_{photon} \frac{1 - \beta \cos(\phi)}{1 - \beta \cos(\theta) + E_{photon} \left(1 - \cos(\theta - \phi)\right) / W}, \tag{1}$$

where $\theta$ is the angle between the scattered photon and the incident particle beam and $W = \gamma m_e c^2$ the particle total energy. Figure 1 shows the relationship for the SuperKEKB HER and LER, assuming a $CO_2$ laser with about 10 $\mu$m wavelength as incident photon source.

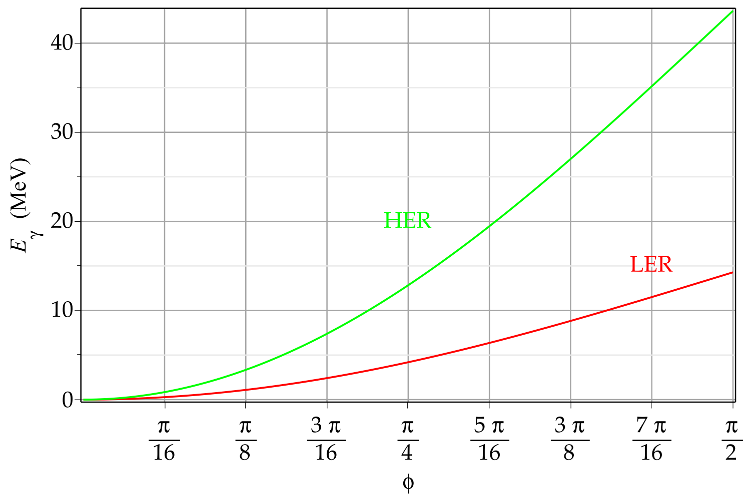


Figure 1: Max. $\gamma$ energy *vs* beam energy for SuperKEKB. Incident photon wavelength is 10.6 $\mu$m

The scattering cross section is sharply peaked forward due to the double Lorentz transformation, and practically speaking independent of the incident angle of the photons in the lab system:

$$\frac{d\sigma}{d\Omega} = -\left(\pi - \arccos\left(\frac{\cos(theta_f) - \beta}{\beta\,\cos(theta_f) - 1}\right)\right)\sqrt{-\beta^2 + 1}\,(\beta\,\cos(theta_f) - 1)^{-1}, \quad (2)$$

shown in Fig. 2.

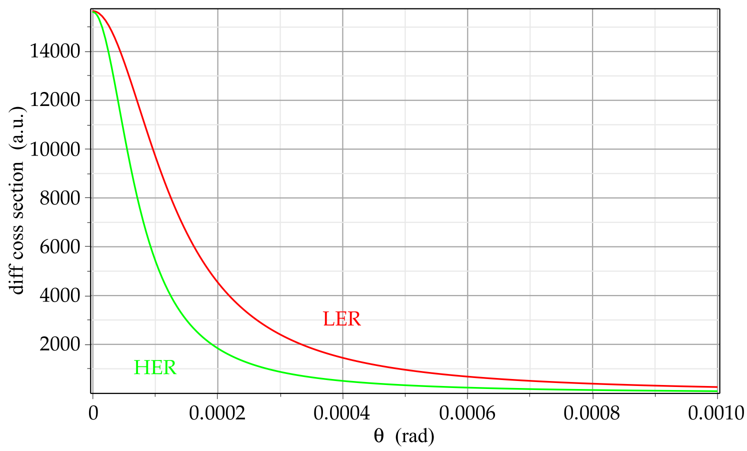


Figure 2: Differential scattering cross section vs angle against particle beam.

The energy spectrum in the lab system for a monochromatic incident photon beam is parabolic, depicted schematically in Fig.??, with a sharp cut-off that is relatively easily detected and analyzed. The max. photon energy ("Compton edge") has a strong dependence on the scattering angle.

$$E_{\gamma,max} = eps\_i\,\gamma^2\,(1 - \beta\,\cos(theta\_i))\left(1 + \frac{\beta\,(\cos(theta\_f) - \beta)}{1 - \beta\,\cos(theta\_f)}\right) \quad (3)$$

$$\cdot\left(1 + \frac{eps\_i\,gammar\,(1 - \beta\,\cos(theta\_i))\,(1 - \cos(\alpha))}{m\_e}\right)^{-1}. \quad (4)$$

It is the energy of this edge that is to be detected and analysed to calculate the electron-beam beam energy. The sharpness of the edge, properly corrected for the detector resolution and other effects, encodes the energy profile of the electron beam.

## 2.2 Detection of the $\gamma$ rays and Calibration issues

The highest-resolution $\gamma$-ray spectroscopy today employs high-purity Ge detectors which are available commercially.[3] These are cryogenic devices operating at $LN_2$ temperatures. A collimator made of a heavy material in front of the detector may be of advantage in keeping a good signal-to-background ratio. We do not need to detect low-energy $\gamma$ rays or X-rays and may use the exit window for the $\gamma$s to absorb radiation below, say, 1 MeV.

Calibration sources will be placed next to the detector to provide ongoing energy calibration. BESSY II uses a combined $^{244}Cm/^{13}C$ source with several lines of known energy. This source provides calibration lines up to about 6 MeV.[4]

This sets the scale for the max. energy of the $\gamma$ rays to be detected. At present, we aim to keep the $\gamma$-ray energy maximum to below 6 MeV for this reason.

# 3 SuperKEKB System

## 3.1 Geometry of the System

From Figure 1 we can read that the system needs to operate at a relatively small incident angle of the laser beam to reduce the energy of the $\gamma$-rays to be detected. For the LER, we may chose an angle of $\pi/4$ or 45° for the Compton edge to be at 4.2 MeV. For the HER, the same geometry would result in about 13 MeV $\gamma$s, too high for an accurate calibration. The HER system would therefore employ an angle of $5*\pi/16$ with a Compton edge at 5.2 MeV. A horizontal crossing angle is chosen to keep the count rate reasonably high. In order to detect the forward $\gamma$-rays, the particles need to be swept away; this is best done with a ring-dipole following the scattering point which therefore should be at a suitable location upstream of such a dipole. Because of the small divergence of the $\gamma$-ray beam the $\gamma$ detector can be mounted at quite a distance from the interaction point without undue loss of count rate. A suitable exit window from the vacuum chamber also absorbs the synchrotron radiation from the dipole.

Inherent in operating at a non head-on geometry is a certain dependence of the $\gamma$ energy on the angle between electron beam and the incident photons. This relation is shown in graphical form in Fig. 3. At $\pi/4$ incident angle, it is about 10 keV/mrad for the LER, for the HER at $5*\pi/16$ it is 20.7. By itself this would require very tight limits on the uncertainty of the angle between electron beam and incident laser beam (about 30 $\mu$rad or less for the LER) to avoid its contribution to dominate the uncertainty. A method to compensate for the effect of this uncertainty is proposed below that allows to recover the accuracy of the method with realistic alignment requirements.

A schematic of the geometry is shown in Fig. **??**

## 3.2 Count rates

An estimate of the expected rates can be made using the known total cross section, 0.663 barn[2] in the Thompson limit, and the geometry of the interac-

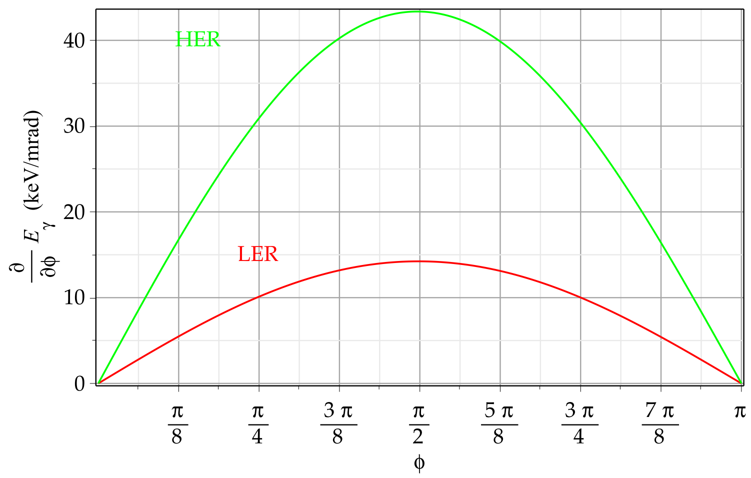


Figure 3: Sensitivity of $\gamma$ energy to incident photon angle.

tion point as well as the intensities of particle beam and laser. Note that in the presence of a crossing angle the rates get significantly reduced compared to head-on collision. A detailed calculation is involved[5]—possibly requiring simulations—and has not been done, but an estimate can be made using the standard luminosity formalism for finite crossing angles. In this way we estimate a total rate of $\gamma$s on the order of 100 kHz for the LER as well as for the HER, for a 10 W $CO_2$ laser and design beam currents, assuming crossing in the horizontal plane, with beam parameters as shown in Table 1. Detector coverage,

Table 1: Beam parameters at the Compton IPs

| Ring | $\sigma_x$ ($\mu$m) | $\sigma_y$ ($\mu$m) | $\sigma_s$ (mm) | $\sigma_{\gamma,x}$ ($\mu$m) | $\sigma_{\gamma,y}$ ($\mu$m) | # photons/s |
|---|---|---|---|---|---|---|
| HER | 325 | 12.5 | 5 | 100 | 100 | $5 \times 10^{20}$ |
| LER | 250 | 13 | 6 | 100 | 100 | $5 \times 10^{20}$ |

collimation and detector efficiency may bring this down by one or two orders of magnitude. Much more detailed estimates need to be made to firm up the expected rate, but at this point rate appears to be sufficient.

## 3.3 Accuracy and energy resolution

### 3.3.1 LER

Typical line width of an HPGe detector is quoted in the industry at about $6 \times 10^{-4}$[3] (1-$\sigma$ line width) at 1.3 MeV, or 2.5 keV at 4.2 MeV $\gamma$ energy. From the reaction kinematics it follows that the apparent width in $dE/E$ of the particle beam is half that, i.e. $3 \times 10^{-4}$ or 1.2 MeV. With enough statistics it stands to reason that we can determine the *central energy* to about 10% of the width. If the calibration of the detector is at the same level of accuracy, this would suggest an absolute accuracy of about 150 keV in the energy calibration. If the incident angle of the laser is uncertain by 30 $\mu$rad, this introduces an uncertainty of another 300 keV, adding this in quadrature would lower the accuracy to about 350 keV.

A "second-order" correction significantly reduces the effect of the uncertainty of the angle between laser and particle beam. It involves moving the laser beam angle by a known amount large compared to its uncertainty (10 mrad, say) and determining $dE_\gamma/d_\phi$. If the angle change of the laser beam can be measured with 150 $\mu$rad precision, and for the same accuracy in energy measurement as above, the relationship used to generate Fig. 3 can be used to derive the actual angle $\phi$ to about 10 $\mu$rad precision. This significantly reduces its effect on the uncertainty of the energy measurement and recovers an accuracy of about 180 keV, now dominated by the detector resolution.

The energy spread measurement will be limited by the detector resolution to about $3 \times 10^{-4}$. There is an effect of the beam divergence, and with a horizontal divergence of about 12.5 $\mu$rad at a $\beta$-function of 20 m at the interaction point this contribution by itself limits the energy resolution to about 100 keV. This effect can be greatly reduced by crossing the particle beam vertically, but at the expense of a reduction in count rate by about a factor of 30. More detailed analysis is needed to firm up this trade-off.

### 3.3.2 HER

For the HER, due to its higher beam energy the situation is slightly less favorable. The line width of the HPGe detector should be 3.1 keV at 5.2 MeV energy. The width in beam energy then goes up to 2.1 MeV and the accuracy can be expected to be about 240 keV from the detector and its calibration. The same correction as proposed above is just as effective and allows determination of this angle to 6.7 $\mu$rad, which bring the accuracy in beam energy to about 260 keV. The beam divergence of the HER, about 16 $\mu$rad, will have a larger influence than in the LER and may force us to either raise $\beta_x$ or adopt vertical crossing, again, this needs further study.

## 3.4 Infrastructure needed

The system would need the following infrastructure in the SuperKEKB facility, per ring.

- Windowed access port to the vacuum system with windows suitable to inject the laser X-rays at the far IR.
- Exit window for the $\gamma$ rays in a dipole chamber.
- $CO_2$ laser, cw, about 10 W average power, about 10 $\mu$ wavelength.

- Beam guidance for the laser X-ray beam, including mirror optics to control the spot size and position of the laser beam at the IP and diagnostics suitable to determine the direction of the laser beam relative to that of the particle beam to better than 100 $\mu$m.
- HPGe detector with $LN_2$ Dewar and associated infrastructure to keep the Dewar filled.
- BPMs suitable to determine the particle beam direction at the IP to better than 100 $\mu$rad relative to that of the electron beam.
- Data acquisition for the HPGe detector and controls for the $CO_2$ laser.

## References

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[3] E.g. Canberra Industries, `http://www.canberra.com/products/detectors/germanium-detectors.asp`,
or Ortec, `http://www.ortec-online.com/Solutions/RadiationDetectors/semiconductor-photon-detectors.aspx`.

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