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Fast and Precise Beam Energy Measurement using Compton Backscattering at e^+e^- Colliders

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Abstract
The report describes a method for fast and precise beam energy measurement in the beam energy range of 0.5-2 GeV and its application at various e^+e^- colliders. Low-energy laser photons interact head-on with the electron or positron beam and produce Compton backscattered photons, whose energy is precisely measured by HPGe detector. The method allows measuring the beam energy with a relative accuracy of $\sim 2{-}5 \cdot 10^{-5}$. The method was successfully applied at VEPP-4M, VEPP-3, VEPP-2000 (BINP, Russia) and BEPC-II (IHEP, China).

Keywords
Compton effect; e^+e^- collider; beam energy measurement; HPGe detector; laser.

1 Motivation

For precise experiments on e^+e^- colliders an accurate beam energy measurement is needed. There are a number of beam energy measurement methods with different precision, time performance and energy range.

For instance, the resonant depolarisation technique is extremely precise; its uncertainty is 10^{-6} of the beam energy. It was applied at various colliders such as VEPP-2, VEPP-4M, LEP, etc., where it gave precise results in high-energy physics (e.g., masses of ω, J/ψ, Z). But the cost of such a precision is a long measurement time (e.g., hours to prepare transverse beam polarisation according to the Sokolov-Ternov mechanism at GeV energy range machines) and technical difficulties (polarisation is very sensitive to beam conditions).

Another method actually is not a beam energy measurement, but worth to be mentioned: collider energy scale calibration using narrow hadron resonances with well-known energy such as J/ψ, ψ(2S), ψ(3770), etc. The precision reaches 10^{-5} of the beam energy in particular points within hours of data-taking time.

Field measurement can be used for rough and very fast energy determination. Usually it is NMR. The energy is calculated: E_0 [MeV] $\approx$ 300 [MeV/T/m] B [T] ρ [m] , where ρ is a bending radius in a field B. The intrinsic accuracy is 10^{-2}, though when calibrated with a more precise method (e.g., resonant depolarisation) and provided with magnet temperature and sextupole field corrections, the method can define the beam energy with a $10^{-3}{-}10^{-4}$ accuracy within some time.

In this report we discuss a fast and precise method based on measuring the energy of the spectrum edge of Compton backscattered photons. It is applicable at the beam energy range of 200–2000 MeV or even wider. This method has an accuracy of $2{-}5 \cdot 10^{-5}$ within 20–60 minutes of data-taking time.

2 Compton backscattering

Compton backscattering (CBS, or inverse Compton effect) in our context, is a head-on inelastic interaction of a low-energy photon and an ultra-relativistic electron (or positron). The scattered photon energy is

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strictly coupled with the scattering angle θ_γ [1]. When $\theta_\gamma = 0$, the photon energy reaches the maximum:

$$\omega_{\max} = \frac{E_0\lambda}{1+\lambda} \approx 4\gamma^2\omega_0\,, \qquad \lambda = \frac{4E_0\omega_0}{m^2}\,, \tag{1}$$

and the scattered electron energy reaches the minimum:

$$E_{\min} = \frac{E_0}{1+\lambda}\,. \tag{2}$$

Here E_0 and γ are the energy and the Lorentz factor of the initial electron, respectively; ω_0 is the initial photon energy; m is the electron rest energy ($c = 1$).

So, the CBS photon spectrum looks like a plateau with a narrow edge at $\omega_{\max}$, see Fig. 1 and Fig. 2, right upper corner.

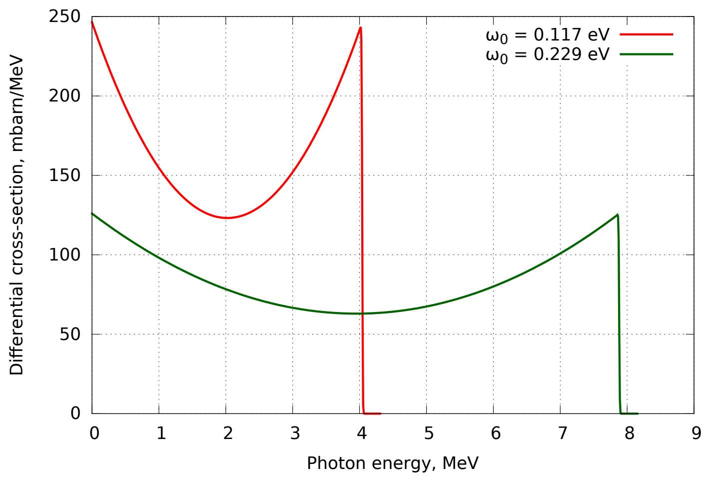

Fig. 1: Theoretical spectrum of Compton backscattered photons. The initial electron energy is 1500 MeV; initial photon energies are 0.117 eV and 0.229 eV (corresponding to particular lasers discussed in this paper).

3 Concept

The procedure of beam energy measurement looks as follows:

- A mid-IR laser beam interacts with an electron (or positron) beam. For this purpose an automated optical system is needed, providing proper focusing and transverse positioning of the laser beam at the interaction point.
- The high-purity germanium (HPGe) detector with an ultimate energy resolution (1–2 keV at 1 MeV, see Fig. 2, middle) registers MeV-range Compton backscattered photons.
- The HPGe detector energy scale is calibrated using monochromatic photons with well-known energies from gamma-emitting isotopes (see Fig. 2, left upper corner). Additionally, the HPGe detector is calibrated using a precision pulse generator to take into account its digital signal processor non-linearity (see Fig. 2, bottom). In Fig. 2 some detector characteristics are shown. For details see particular experiment papers referred in Section 4.
- The energy of the Compton spectrum edge (Fig. 2, right upper corner) is found and the beam energy is calculated according to equation 1:

$$E_0 = \frac{\omega_{\max}}{2}\left(1 + \sqrt{1 + \frac{m^2}{\omega_0\omega_{\max}}}\right) \approx \frac{m}{2}\sqrt{\frac{\omega_{\max}}{\omega_0}}\,. \tag{3}$$

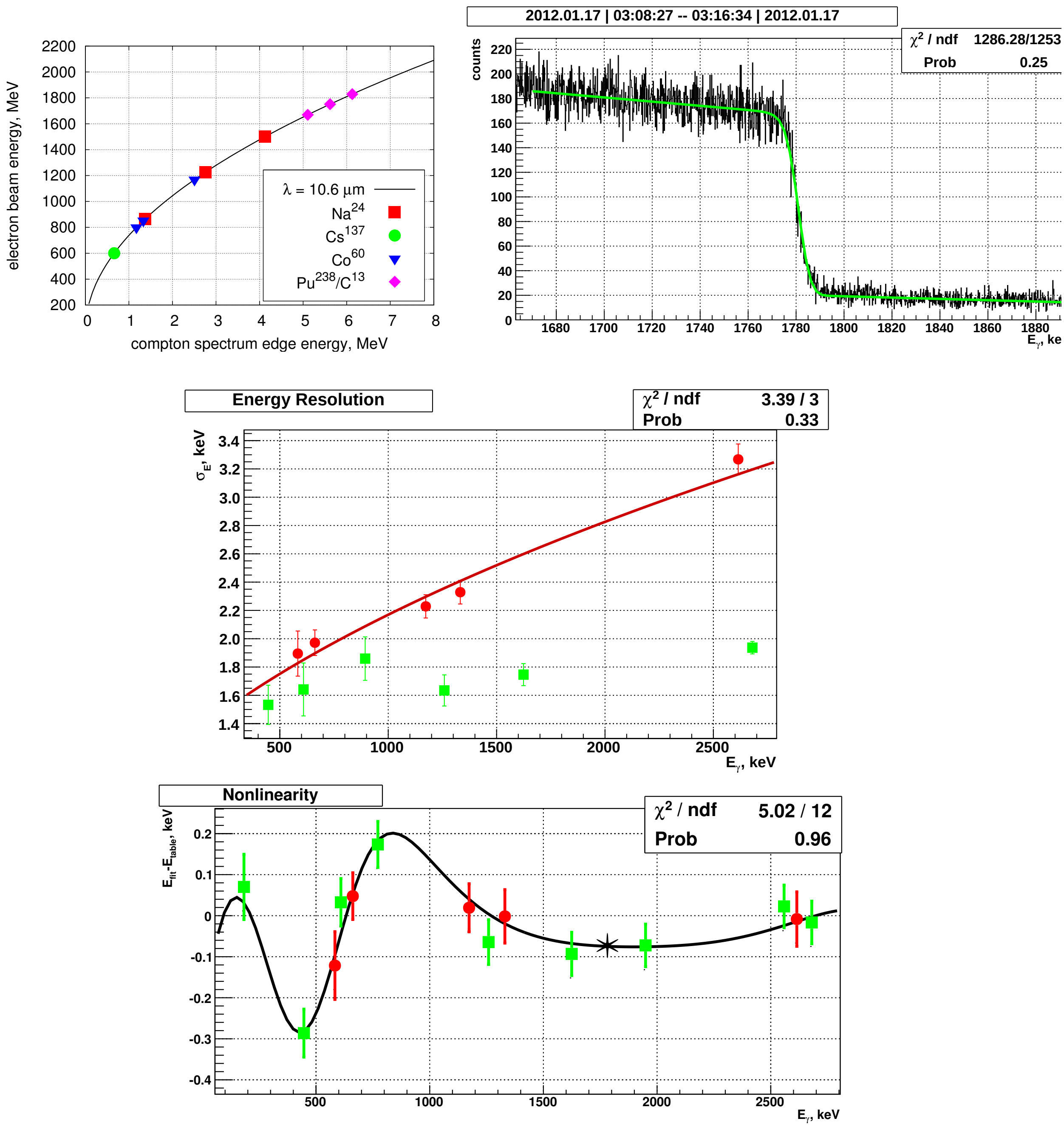

Fig. 2: HPGe detector characteristics and performance. Top left: energies of isotopes used for energy scale calibration vs. corresponding beam energy (CBS with 10 μm laser). Top right: CBS photon spectrum edge. Middle: detector energy resolution. Bottom: detector residual nonlinearity; solid curve: nonlinearity measured with a precision pulse generator; asterisk: $\omega_{\max}$ with 10 μm laser and 1.0 GeV electron beam energy. In the latter two plots, red circles: isotopes photopeaks; green squares: precision pulse generator peaks. Source: Ref. [2].

– The uncertainty of the beam energy is

$$\frac{\Delta E_0}{E_0} \simeq \sqrt{\left(\frac{1}{2}\frac{\Delta\omega_{\text{max}}}{\omega_{\text{max}}}\right)^2 + \left(\frac{1}{2}\frac{\Delta\omega_0}{\omega_0}\right)^2 + \left(\frac{\Delta m}{m}\right)^2}. \tag{4}$$

The uncertainty is mostly defined by the first term. It comprises detector issues, such as energy scale calibration, response function, etc., and the beam energy spread. The second term is the uncertainty and stability of the laser photon energy; the third term is the extremely small uncertainty of the electron rest energy. Both of them do not exceed 10^{-7}. The total beam energy uncertainty is typically $5 \cdot 10^{-5}$.

– Additionally, the beam energy spread can be found with an accuracy of 10% through measuring the spectrum edge width and deconvolving the detector response function.

4 Implementation

At the first time the method under discussion was implemented at the «Taiwan Light Source» SR ring in 1996, see Ref. [3]. There a 0.1% precision was achieved at a beam energy 1300 MeV. At the end of the nineties the method was applied at the SR ring BESSY-I in Berlin, and later at the successor, BESSY-II, see Refs. [4, 5]. The accuracy achieved was $3 \cdot 10^{-5}$. The latter results showed that the method under discussion could be sufficient for colliders, especially for precise high-energy physics. It was decided to apply the method at BINP colliders and other installations. In this section the beam energy measurement facilities created by BINP team in 2005–2014 are discussed.

4.1 VEPP-4M

VEPP-4M at Budker Institute of Nuclear Physics (Novosibirsk, Russian Federation) is the e^+e^- collider with beam energies of 1.5 GeV to 5.5 GeV designed for precise experiments such as measurement of τ-lepton, J/ψ, ψ(2S), ψ(3770) masses and R (the ratio of total hadrons production cross-section to that of leptons) at the KEDR detector. For this purpose the beam energy is measured by resonant depolarisation technique at some energies. At the τ threshold and some other important points the beam polarisation is destroyed by the machine resonances, and thus another beam energy measurement method was needed. In 2005 the CBS installation was constructed at VEPP-4M. It was in operation until 2014. The layout of the installation is shown in Fig. 3. Since both electron and positron beams move in the same magnet system, only the electron beam energy was measured. A CO_2 laser with a wavelength of 10.56 μm ($\omega_0 = 0.117$ eV), 50 W CW power was used.

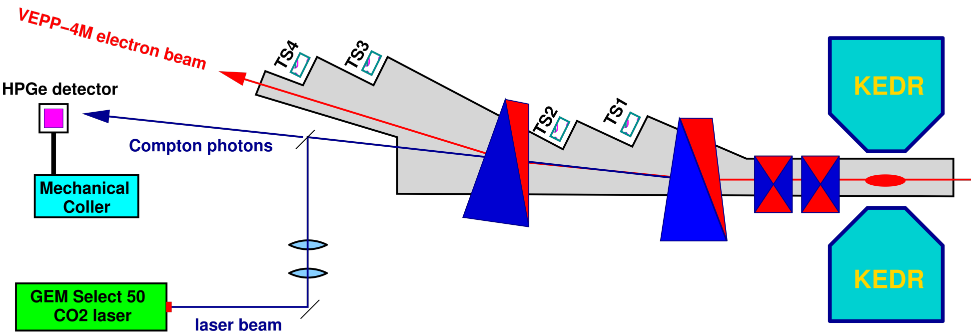

Fig. 3: Layout of the CBS facility at VEPP-4M

In this experiment the best accuracy of the method was $2 \cdot 10^{-5}$ (1.5 hours of data-taking); typical accuracy was $4 \cdot 10^{-5}$ (within 20 minutes). This accuracy was confirmed in simultaneous beam energy measurement by the resonant depolarisation technique. More details can be found in Ref. [6].

The method was used in a precise τ-lepton mass measurement, see Ref. [7].

4.2 VEPP-3

An experimental study of electromagnetic form factors of the proton was performed at the VEPP-3 storage ring at BINP in 2009–2012. The goal of the experiment was to measure the two-photon contribution in elastic ep scattering through comparison of the e^-p and e^+p scattering cross-sections. The electron and positron beams were scattered one by one on cold polarised protons. The beam energy was 1.0 GeV and 1.6 GeV. To reduce systematic errors, the e^+ and e^- beam conditions should be as identical as possible; for instance, the e^+ and e^- energy difference should be kept less than 1 MeV (10^{-3}). For this task the CBS method was applied for VEPP-3 beam energy measurement. A layout of the facility is shown in Fig. 4. The CO_2 laser mentioned above (10.56 μm, 50 W CW) was used.

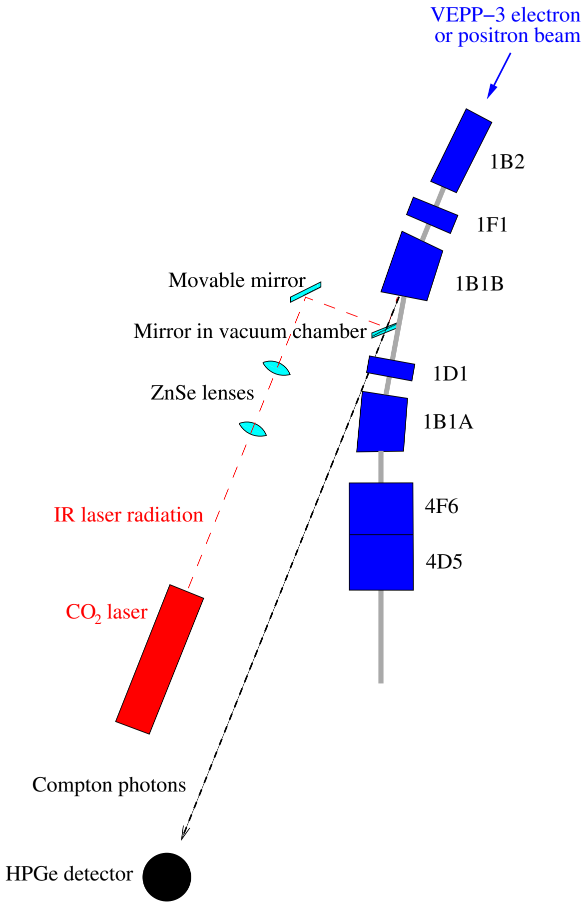

Fig. 4: Layout of the CBS facility at VEPP-3. Source: Ref. [2]

Here a precision pulse generator was applied for the first time for the detector energy scale calibration in the experiments under discussion. It allows measuring the nonlinearity of the HPGe detector multi-channel analyser (a digital signal processor for acquiring photon energies from the detector), which appeared to be a major source of integral nonlinearity. Fig. 2, bottom, shows this residual nonlinearity. These measures improved the calibration precision to a level of 10^{-4} or even better.

The typical accuracy of the beam energy measurement was $5 \cdot 10^{-5}$. See long-term energy behaviour in Fig. 5. More details of the experiment can be found in Ref. [8]; more details of the CBS method implementation can be found in Ref. [2].

4.3 BEPC-II

BEPC-II at IHEP (Beijing, China) is a high luminosity e^+e^- collider in the energy region of 1–2 GeV. Precise experiments on τ, J/ψ, ψ(2S) with the BES-II detector required accurate beam energy mea-

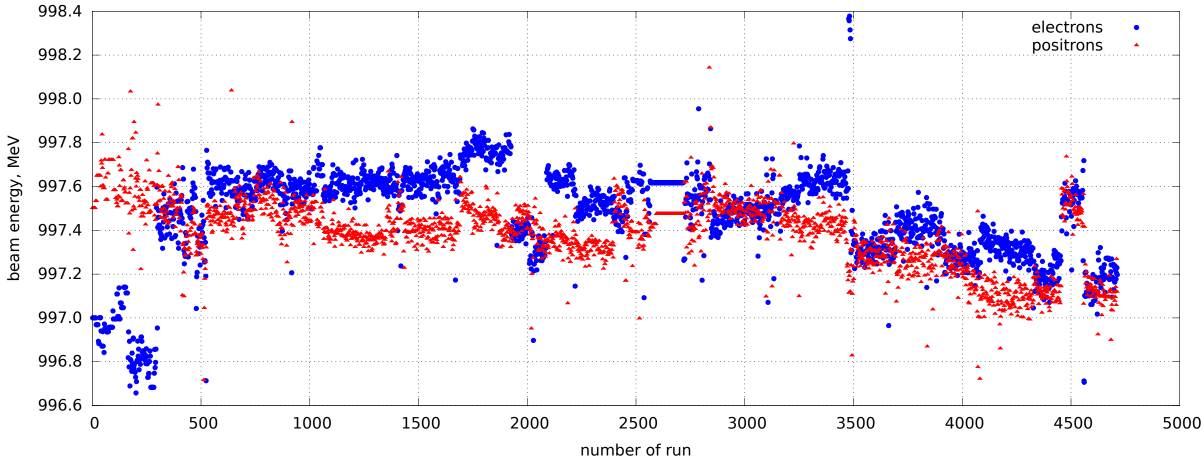

Fig. 5: VEPP-3 beam energy behavior. Source: Ref. [2]

surement. Because of the strong depolarization impact (due to the increased luminosity), the resonant depolarisation technique is not applicable. The CBS beam energy measurement system was installed in 2010. BEPC-II has two separate beamlines for positrons and electrons. It was decided to use one CO_2 laser ($\lambda_0 = 10.84\ \mu$m, $\omega_0 = 0.114$ eV, 50 W) and one HPGe detector for measuring the energies of both beams, as shown in Fig. 6.

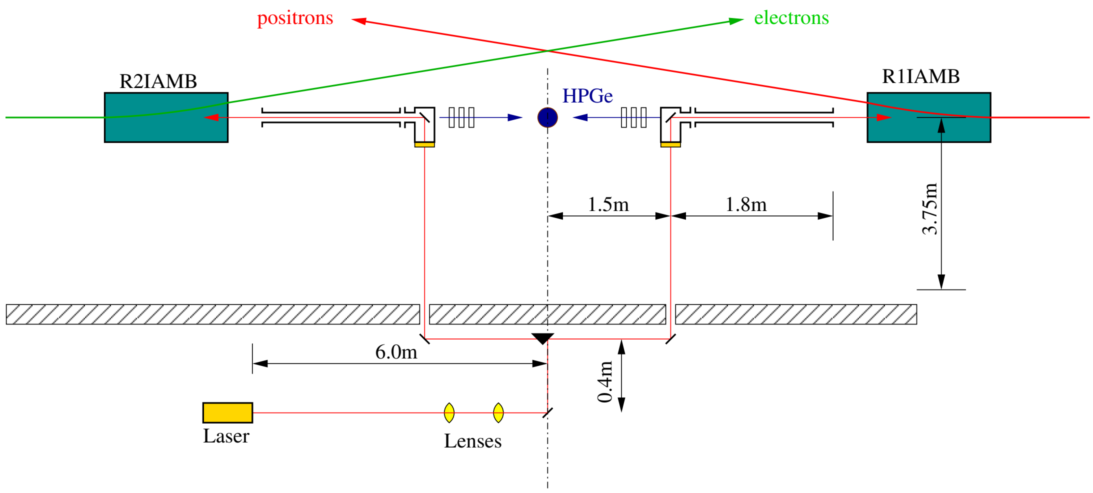

Fig. 6: Layout of the CBS facility at BEPC-II. Source: Ref. [9]

The typical accuracy of the beam energy measurement was $5 \cdot 10^{-5}$; the accuracy was measured using a scan of narrow hadron resonances. More details of the method can be found in Ref. [9]. Some precise results at the BES-III detector (e.g., τ lepton mass) are shown in Ref. [10].

4.4 VEPP-2000

In 2012 the CBS facility was constructed at VEPP-2000 (BINP), the e^+e^- collider operating in the beam energy range of 0.5–1.0 GeV for precise experiments with the SND and CMD-3 detectors. A CO_2 laser ($\lambda_0 = 10.56\ \mu$m, $\omega_0 = 0.117$ eV, 50 W) and CO laser ($\lambda_0 \sim 5\ \mu$m, 2 W) were used. The Compton interaction occurs in the dipole magnet, see Fig. 7, top, unlike similar CBS facilities described in this paper. This fact led to an unusual Compton spectrum shape: a wider edge and distinguishable oscillations, see Fig. 7, bottom.

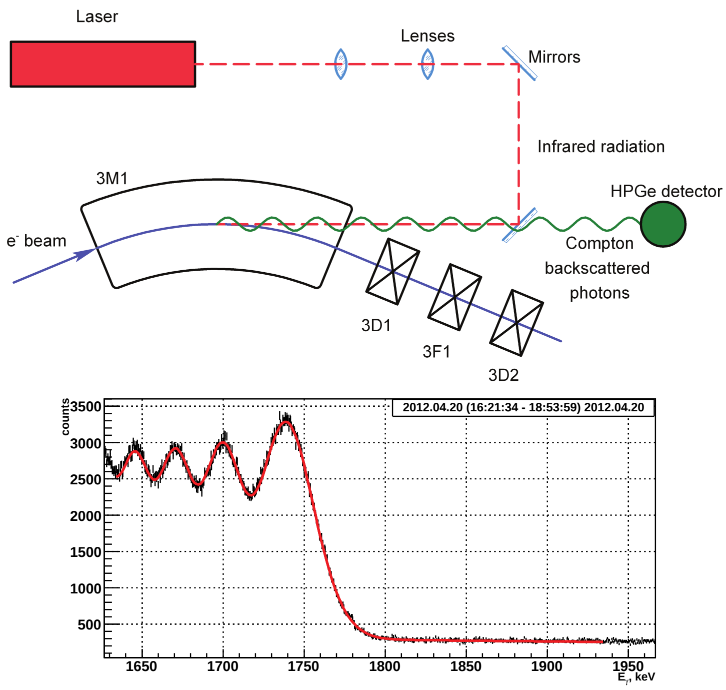

Fig. 7: Top: layout of the CBS facility at VEPP-2000. Bottom: observed spectrum of CBS photons. Source: Ref. [12].

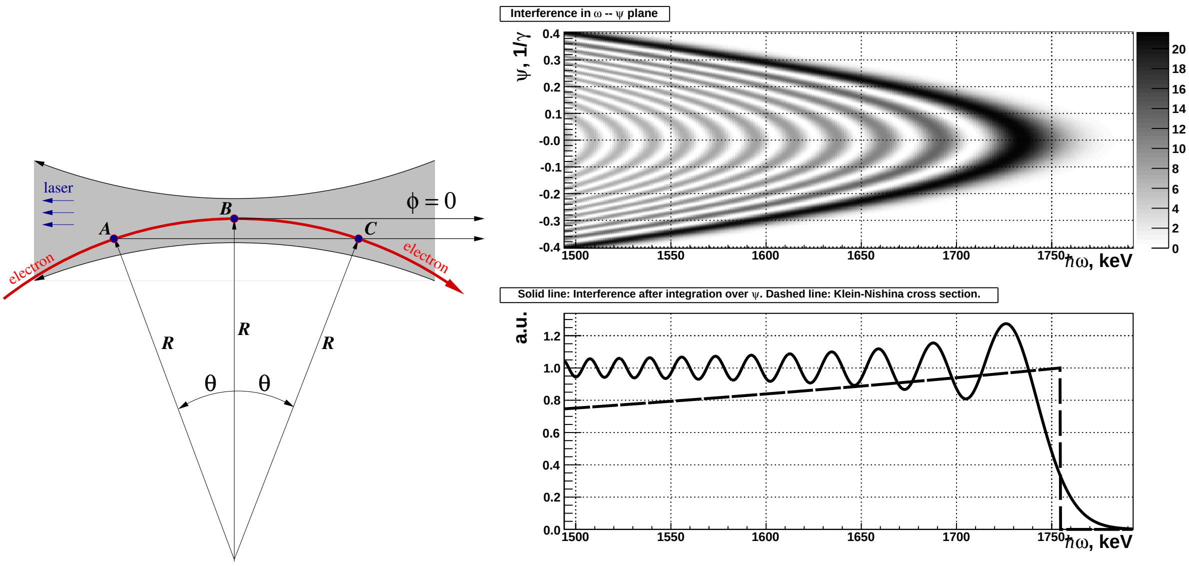

Fig. 8: Interference of MeV-range photons in CBS in magnetic field. Left: layout of formation of the interference. Right top: 2D view, angle vs. energy; right bottom: result of integration. Source: Ref. [12].

This unusual spectrum shape is indeed a newly observed phenomenon. Unlike previous experiments, here the photon interacts with the electron in a magnetic field, and thus the electron can be treated as a bound one. The phenomenon can be described both in QED and quasi-classical frameworks. The quantum solution is derived from the Dirac equation in Ref. [11]. In the quasi-classical approach the phenomenon can be treated as interference of MeV-range photons emitted in an arc electron trajectory (see Fig. 8 and Ref. [12], details of the experiment at VEPP-2000 can also be found there). Multiplied by the Klein-Nishina cross-section, a quasi-classical expression becomes similar to a quantum one with a slight difference: the difference in energy is less than 10^{-6}. The theory is in a good agreement with the experiments, see the analytically defined function and the spectrum in Fig. 7, bottom. Some precise results obtained at the CMD-3 detector are given in Ref. [13]

5 Conclusion

- Beam energy measurement using the spectrum edge of Compton backscattering photons was successfully implemented at various accelerators and colliders: VEPP-4M, VEPP-3, VEPP-2000, and BEPC-II. The BINP team has a large experience.
- The method is fast, precise, and non-invasive and does not require special beam conditions.
- The method has an accuracy of $2-5 \cdot 10^{-5}$ of the beam energy, which can be achieved within 20–120 minutes of data-taking time.
- The method can be applied at various low-energy $e^{\pm}$ accelerators, including the Super charm-tau Factory (project of a high-luminosity 1–5 GeV $e^{+}e^{-}$ collider at BINP).
- Interference of MeV-range photons was observed.

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