Upgrade of beam energy measurement system at BEPC-II *

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Abstract: The beam energy measurement system is of great importance for both BEPC-II accelerator and BES-III detector. The system is based on measuring the energies of Compton back-scattered photons. In order to meet the requirements of data taking and improve the measurement accuracy, the system has continued to be upgraded, which involves the updating of laser and optics subsystems, replacement of a view-port of the laser to the vacuum insertion subsystem, the use of an electric cooling system for a high purity germanium detector, and improvement of the data acquisition and processing subsystem. The upgrade system guarantees the smooth and efficient measurement of beam energy at BEPC-II and enables accurate offline energy values for further physics analysis at BES-III.

Keywords: laser, HPGe detector, beam energy measurement

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1 Introduction

The upgraded Beijing Electron-Positron Collider (BEPC-II) is a τ-charm factory with a center-of-mass energy ranging from 2.0 to 4.6 GeV and a design peak luminosity of $10^{33} \text{cm}^{-2} \text{s}^{-1}$ [1, 2] at the center-of-mass energy of 3.770 GeV. The upgraded Beijing Spectrometer detector (BES-III), with high efficiency and good resolution for measuring both charged and neutral particles, started data taking in 2008 [3, 4].

After large amounts of data are acquired and analyzed, the statistical uncertainties in physics analysis become smaller and smaller, while the systematic uncertainties play a more and more prominent role [5−7], especially the uncertainty due to the measurement of beam energy. Starting from the year 2007, a high accuracy beam energy measurement system (BEMS) located at the north crossing point (NCP) of BEPC-II was designed, constructed, and put into the commissioning at the end of 2010 [8−11]. Two days were used to perform the $\psi'$ scan. The mass difference between the PDG(2010) value and the measured result by BEMS is 1±36 keV, the deviation of which indicates that the relative accuracy of BEMS is at the level of $2 \times 10^{-5}$ [10].

BEMS improves the measurement capability of both accelerator and detector, and can measure the beam energy, energy spread and their corresponding errors, all of which are crucial information for the physics analysis of BES-III and the luminosity tuning at BEPC-II. The first test scan of the $\tau$ mass was performed at the end of 2011. The integrated luminosity of the $\tau$ sample was 23.26 pb$^{-1}$, and the mass of the $\tau$ lepton was determined as $m_{\tau} = 1776.91 \pm 0.12^{+0.10}_{-0.13}$ MeV [12], in which the systematic uncertainty due to energy scale is less than 0.09 MeV.

During five years’ running, BEMS was used in various data collections at BES-III, including the J/ψ and $\psi'$ resonance samples, $R$ value scan samples and high excited charmonium states samples. The high precision beam energy values were measured and are very useful for offline data analysis.

The high precision energy calibration acquired by BEMS is based on the Compton backscattering principle. The working scheme of this system can be recapitulated.

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as follows [13]: firstly, a laser source provides a laser beam and an optics system focuses the laser beam and guides it to collide with the electron (or positron) beam in the vacuum pipe, where the Compton backscattering process happens; after that the backscattering high energy photons are detected by a HPGe detector. More engineering details can be found in Ref. [10]. The whole system can be sub-divided into four parts: 1) laser and optics system, which supplies low energy laser and focused photons; 2) laser to vacuum insertion system, where a laser beam collides with a electron (or positron) beam; 3) HPGe detector to measure backscattering high energy photons; 4) data acquisition and running control system for information processing and analysis. The layout schematic of the system is shown in Fig. 1.

![Simplified schematic of beam energy measurement system.](image)

In order to meet the physics requirements, and improve the measurement accuracy, updates for BEMS have been performed since its commissioning. The details are described in the following sections. The laser and optical system upgrade is introduced in Section 2. The improvement of the laser to vacuum insertion system is presented in Section 3. The update of the detection system is introduced in Section 4. The data acquisition and processing system are presented in Section 5. The interlock system is introduced in Section 6. The upgrade effect is shown in Section 7. Finally, there is a short summary.

## 2 Laser and optical system

This system consists of a laser source to supply low energy photons, two lenses to focus the beam light, three reflecting mirrors, and one movable prism to direct the laser beam into the storage ring tunnel. All relevant instruments are installed outside the shielding concrete wall as shown in Fig. 1. The upgrade processes are described chronologically below.

### 2.1 Lenses upgrade

The laser beam is focused at the BEPC-II vacuum chamber entrance flange, where the geometrical aperture is minimal: vertical size × horizontal size is 14 mm × 50 mm. Since the total distance from the laser output aperture to the entrance flange of the BEPC-II vacuum chamber is about 18 m, the focusing is realized by two lenses.

Previously, a doublet of ZnSe lenses with focal length of 40 cm were placed at distances of 300.0 cm and 381.6 cm from the laser output window. They provided a laser beam transverse size at the flange from 2.0 to 2.5 mm for collision. The laser transmissivity for the two lenses were 69% and 61% respectively. The synthetic transmissivity was merely 42%, which means more than half the photons were consumed during the focusing.

Two new ZnSe lenses were manufactured. The focal length of these lens is 42 cm, and they are placed at 330 cm and 415 cm in front of the laser output window for the laser focusing. The transmissivity to laser is 99% for each lens. Very few photons are wasted on focusing, and more photons are guided into the vacuum pipe to collide with the electron (or positron) beams.

### 2.2 Prism replacement

During the operation of BEMS, the energy of the electron and positron beam are measured alternately. The alternation is executed by a translatory reflector prism, as shown in Fig. 2, where (a) and (b) are a schematic explanation for beam path selection, and (c) is the translatory prism. The laser beam is directed by the prism towards the left or right mirror to collide with the electron or positron beam depending on the prism position. After several years, dust accumulated in the groove of the prism support gave a braking effect on the automatic movement and eventually led to the immobilization of the prism. As a result, the switch between electron and positron beam had to be manipulated manually, which is impractical for full-day continuous measurement.

Instead of replacing the old prism with a new one, a brand new design was proposed to prevent recurrence of the problem. A rotary platform as shown in Fig. 2(f) was applied. The rotary gear was covered below the platform to ensure it was dust-free. A through hole at the center of the rotary platform strictly satisfied the coaxial requirement with the center of rotation. The absolute positioning accuracy of the rotary platform is 0.005 degrees. A special support was designed, forged, and installed to fix the rotary platform. A mirror with its frame was fixed on the rotary platform to change the direction of the laser. The rotary platform is controlled by a step motor, whose step is 1.5×10⁻⁶ rad. The rotation angle of the mirror is controlled precisely, so that the laser will be reflected...
to the left or right to collide with electron or positron beam.

![Diagram](image)

Fig. 2. (color online) The left side is the translatory prism and the right side is the rotary platform. The laser light, represented by the dashed line, is reflected to the electron (a, d) and positron (b, e) side using translatory prism and rotary platform respectively. The translatory prism and the rotary platform are shown in (c) and (f).

2.3 Laser improvement

The laser source of initial photons is produced by a GEM selected 50\textsuperscript{TM} \textsuperscript{TM} CO\textsubscript{2} laser from Coherent, Inc. It is a continuous operation (CW), high power, single-line narrow-width laser. It provides 25 W of CW power at a wavelength $\lambda_0 = 10.835231 \text{\mu m}$ ($\gamma$-quantum energy $\omega_0 = 0.114426901 \text{eV}$) \cite{14}. The relative accuracy of $\omega_0$ is better than 0.1 ppm.

After five years’ running, the grating coat wore too thin, so the photons interacting with the beam in the collider became too weak. The laser was returned to the factory for repair. Considering that the design beam current of BEPC-II is 910 mA, the requested physics energy region ($1.0 - 2.3 \text{ GeV}$) is wide, and the background near the NCP is complicated, a more powerful laser is needed. Therefore, a more powerful laser with output power up to 50 W was chosen. The wavelength of the new laser is $\lambda_0 = 10.591035 \text{\mu m}$ ($\gamma$-quantum energy $\omega_0 = 0.117065228 \text{eV}$) \cite{14}.

The power of the new laser is about twice that of the old one, so that more laser photons are gathered at the interaction region and collide with the beam. Therefore, the Compton edge will be easier to obtain, and the data taking time for measurement will be shortened.

![Diagram](image)

Fig. 3. (color online) Schematic diagram of the laser to vacuum insertion of BEMS. SR represents the synchrotron radiation light.

3 Laser to vacuum insertion system

The laser to vacuum insertion system \cite{15} is a crucial part of BEMS. As shown in Fig. 3, the system is composed of a special stainless vacuum chamber with entrance viewport and a reflecting copper mirror. From this part, the laser beam is inserted into the vacuum chamber, reflected 90 degrees by the copper mirror and collides with the electron (or positron) beam. Then the back-scattered photons pass through the copper mirror and are detected by the HPGe detector. Since the mirror is heated by laser and synchrotron light, it must be cooled by cooling water. In addition, since this part connects with the beam pipe of the storage ring, after installation, the vacuum chamber must be baked at 250 degrees for 24 hours in order to guarantee that the vacuum pressure is better than $2 \times 10^{-10} \text{Torr}$.

In Fig. 1, it can be noted that the beam of electrons (or positrons) is bent at the NCP. The collision between laser and beam happens just before the bend, which avoids the interference of beam current with backscattering photons. At the same time, the synchrotron light radiates along the tangent direction of the bent beam and the path of this synchrotron light is the same path as that of the laser beam but in the opposite direction (refer to Fig. 3). Therefore, the synchrotron light can be used to pin down the laser beam alignment. The actual process of light path adjustment is as follows.

The copper mirror is mounted on a special copper support, which can be tuned by bending the vacuum flexible bellows using a screwdriver. The back panel of the copper support is shown schematically in Fig. 4(a), where the positions of the four screws are denoted. The
adjustment for the horizontal and the vertical directions are realized by two pairs of screws separately. The adjustment distance $l$ can be calculated as follows when the screw rotates one circle:

$$\frac{d}{D} = \frac{l}{L}, \quad (1)$$

where $d = 0.5$ mm is the one circle distance for the screw; $D$ is the dimension of the support, which is 70 mm for the vertical support and 39 mm for the horizontal one; $L = 4150$ mm is the distance between the copper mirror and the hole in the wall. During the running period of BEPC-II, the synchrotron light spots are visible. Two cameras are installed, the west for electrons and the east for positrons. Comparing with the one circle distance obtained using Eq. (1), the number of turns can be evaluated, then the optical path can be adjusted accordingly. The cartoon drawn in Fig. 4(b) shows schematically the tuning of the optical path. Usually tuning one or two times is enough. The actual adjustment effects are displayed in Fig. 4 (c) and (d) by means of the cameras. It is clear that after the mirror adjustment, the synchrotron light passes through into the holes in the wall and is reflected to where the laser will pass. Similarly, the laser can be transferred through the hole and reflected into the collider to collide with the beam.

As shown in Fig. 3, the entrance viewport is crucial for the laser to vacuum insertion system, since it is in charge of the light path adjustment and the laser beam insertion. The viewport must be transparent to both laser beam and synchrotron light. Two types of entrance viewports [16, 17] were used sequentially by BEMS, one based on gallium arsenide (GaAs) monocrystal plate and the other on zinc selenide (ZnSe) polycrystal plate.

At the beginning, a GaAs plate with diameter of 50.8 mm and thickness of 3 mm was used by BEMS. However, the GaAs crystal is not transparent to visible light, it transmits infrared radiation. In order to detect the spots of infrared light, IR-sensitive video cameras were used. During the BEMS running, the GaAs viewport was changed three times to improve the transmissivity of the window. Finally a ZnSe plate with thickness of 8 mm was adopted. The laser transmission rate rose from 60% to 76%. In addition, more visible synchrotron light is transparent, which is convenient for the optical path adjustment.

4 HPGe detection system

The backscattering high energy photons are detected by the HPGe detector, which is the key instrument of BEMS. The accuracy of beam energy depends solely on the detection results of the HPGe detector. There are two crucial conditions for HPGe detector to function properly and enduringly for BEMS, that is low temperature environment and radiation protection. The upgrades of these two aspects are described below.

4.1 Cryogenic system upgrade

4.1.1 HPGe detector

A $p$-type coaxial HPGe detector manufactured by ORTEC (model GEM25P4-70) is used by BEMS. Its energy resolution for the 1.33 MeV peak of $^{60}$Co is 1.74 keV, and the relative efficiency is 25%. The detector is connected to the multichannel analyzer of the ORTEC DSpec Pro(MCA), which transfers data using the USB port of the computer.

4.1.2 Two cryogenic systems

Low temperature is crucial for HPGe detectors to function properly [18–20]. Two approaches are usually employed to get the temperature below 100 K : liquid nitrogen (LN$_2$) and electric coolers [21]. The former was used first for cooling the HPGe detector at BEMS.

One common LN$_2$ filling method, namely the self-pressurizing technique, was used by BEMS. More details
about this method can be found in Ref. [22]. During the data taking period of BES-III, BEMS is kept running simultaneously. The LN$_2$ has to be supplied once a week to avoid unexpected warm-ups of the HPGe detector. However, such a regular filling schedule is unfavorable to both the BES-III detector and BEPC-II accelerator as data taking time has to be consumed for refilling LN$_2$.

From the point of view of continuous cooling, an electric cooler is an ideal replacement for the LN$_2$. An electric cooler, composed of a compressor, transfer hose, heat exchanger, and cold head, was adopted for the HPGe detector. The only concern here is the continuous electricity power, so that an uninterruptible power system (UPS) is used for the cooler.

### 4.1.3 Resolution comparison of two cryogenic systems

An electric cooler was once the first choice for BEMS, but the resolution of HPGe under such a cryogenic system should be checked carefully. A laboratory experiment was designed and performed [22] to investigate the resolution under the two cryogenic conditions.

During the experiment, a point-like radiation source of $^{152}$Eu, whose main lines are from a hundred keV to 1.4 MeV [23, 24], was placed along the cylindrical center axis of the germanium crystal, and about 1 cm from the top of the germanium detector. A 1 cm foam plate was inserted between the source and the detector. The HPGe detector was calibrated by $^{137}$Cs and $^{60}$Co before experiment.

The experiment began with the electric cooler case. About three days’ data were collected after the HPGe was exposed to the radiation source. In order to remove the background effect, 3 days’ background data were taken before and after the $^{152}$Eu nuclide measurement, separately.

After the above experiment, the PopTop capsule of the detector was removed from the cold head of the electric cooler, then connected with the cryostat, and put into a dewar filled with LN$_2$. After about 6 hours cooling, the germanium crystal was cold enough to apply the high voltage to bias the detector. The detector was calibrated using $^{137}$Cs and $^{60}$Co before $^{152}$Eu measurement under the LN$_2$ cooling condition. The radiation source experiment was performed for about three days. Also the background data of about 3 days were taken before and after the measurement of $^{152}$Eu under the LN$_2$ cooling, respectively.

The comparison of the detector resolutions to the characteristic lines of $^{152}$Eu under the different cooling methods are shown in Fig. 5. As described in Ref. [22], the shape of the lines are almost same, but the resolution of the germanium detector using the electric cooler is about 10% better than that using the LN$_2$. The noise level for both LN$_2$ and electric cooler is the same, about 10 keV.

The laboratory measurements indicate that the resolution of the HPGe detector using the electrical cooler is better than using liquid nitrogen cooling. Therefore, the electric cooler was installed in the summer of 2013 to replace the LN$_2$ cooling.

![Fig. 5. (color online) The comparison of the detector resolutions to the characteristic lines of $^{152}$Eu under LN$_2$ cooling method represent as dot and electric cooler method indicated as circle.](image-url)

### 4.2 Alternating moving shielding

Since the HPGe detector is located near the beam pipes of the collider, the radiation background due to beam loss is extremely high [25, 26]. In order to protect the HPGe detector from radiation damage, a special design of radiation protect is indispensable [25]. In actual running periods, the detector is surrounded by 5 cm of lead on all the sides, by 1.5 cm of iron below, and by 5 cm of lead above. Moreover, it is also shielded by 10 cm of paraffin on all sides. Since the main radiation background comes from the beam direction, an additional 11 cm of lead is installed in the beam direction [10].

However, even with the above protections, the radiation background along the beam direction seems still high. For improvement, an alternating moving shielding device was designed for further protection. As shown in Fig. 6(a), two movable stages with 10 cm thickness of lead were fixed on an aluminum electric push rod which can move in a range of 350 mm with movement speed of 8 mm per second. The electric push rod was installed between the HPGe detector and the short vacuum chamber as shown in Fig. 3. If needed, the lead can move into the beam direction to shield the high energy photons coming from the other direction. For example, assuming the energy of the positron beam need to be measured, the movable leads at the positron side (east side) will move out from the beam direction, and the backscattered photons will enter into the sensitive volume of germanium detector for measurement. However the electron side (west side) movable leads will move into the beam direction to shield the radiation photons from the electron beam. The working flow chart of the movable shielding is shown in Fig. 6(b).
The actual data acquisition system is executed automatically, which is controlled by software. Its working procedure is as follows. First, some requirements (such as data taken time, data type, or energy difference range) are input as parameters into the software, then the software queries the BEPCII database and gets the status parameters of the accelerator, such as beam currents, lifetime, energy value and so on. Then the HPGe detector begins to take data. Every few seconds, the HPGe detector measurements are stored and the detector counting rate is calculated. The mirrors are adjusted automatically to a position with a maximal photon/beam interaction using the feedback from the detector counting rate.

If the status of the accelerator is changed sufficiently, such as energy drift or beam loss, the current data is saved, then the next spectrum acquisition cycle is launched. Simultaneously, another program processes the saved data, calibrates the energy scale, finds the Compton edge, and calculates the beam energy. The beam energy is written into the BEPC-II database.

The measurement will switch to the other side of the beam when the requested data acquisition time has finished or the status of measured beam does not satisfy the requirement. The rotary platform will turn a certain degree and direct the laser into the other side of the vacuum chamber for collision. The movable shielding leads as described in section 4.2 will move in or out the beam direction according to the requirement. All these adjustments are operated automatically.

5.2 Calibration improvement

The kernel of the data acquisition system lies in the data processing, which is composed of three parts namely calibration of energy scale, Compton edge fitting, and determination of beam energy. The improvement mainly consists in the response function and calibration source.

5.2.1 Response function and edge fitting

The goal of calibration is to obtain the coefficients needed for conversion of the detector’s ADC counts into corresponding energy deposition, measured in units of keV, as well as determination of the detector’s response function parameters. The following response function was used:

\[ f(x, x_0, \sigma, \xi) = A \left\{ \begin{array}{ll}
\exp\left\{ -\frac{(x-x_0)^2}{2\sigma^2} \right\}, & x > x_0 - \xi \cdot \sigma \\
\exp\left\{ -\frac{\xi^2}{2} \cdot \frac{x - x_0}{\sigma} \right\}, & x < x_0 - \xi \cdot \sigma,
\end{array} \right. \]

where \( A \) is amplitude with normalization, \( x_0 \) is the position of peak, \( \xi \) is an asymmetry parameter, and \( \sigma \) is the full width of Gaussian distribution at half maximum divided by 2.36.
The edge of backscattered photons spectrum is fitted by the function:

$$S_2(x, x_0, \sigma, \sigma_x, \xi) = \int_{-\infty}^{+\infty} S_1(y, x_0, \sigma, \sigma_x, \xi) dy + p_1(x). \quad (5)$$

Here $p_1(x)$ takes into account the background contribution and $S_1$ is a convolution of the step function $\theta(x_0-x)$:

$$\theta(x_0-x) = \begin{cases} 
1, & x < x_0 \\
0, & x > x_0,
\end{cases} \quad (6)$$

which describes the “pure” edge shape with the HPGe detector response function (4) and Gaussian:

$$g(x, x_0, \sigma) = \frac{1}{2\pi \sigma} \exp \left\{ -\frac{(x-x_0)^2}{2\sigma^2} \right\}. \quad (7)$$

which takes into account the energy spread of backscattered photons due to the energy distribution of the collider beam.

$$S_1(x, x_0, \sigma, \sigma_x, \xi) = \frac{N}{\sqrt{2\pi}}$$

$$\times \left\{ \frac{1}{\sigma} \exp \left( \frac{\xi^2}{2(1+\sigma^2/\sigma_x^2)} + \frac{\xi x}{\sigma} + \frac{(\sigma^2+\sigma_x^2)}{\sqrt{2}\sigma_x} \right) \cdot \text{erfc} \left( \frac{\xi(\sigma^2+\sigma_x^2)+\sigma x}{\sqrt{2}\sigma_x} \right) \right\}$$

$$+ \frac{1}{\sigma^2+\sigma_x^2} \exp \left( -\frac{\sigma^2}{2(\sigma^2+\sigma_x^2)} \right) \cdot \text{erfc} \left( -\frac{\xi(\sigma^2+\sigma_x^2)+\sigma x}{\sqrt{2}(\sigma^2+\sigma_x^2)\sigma_x} \right). \quad (8)$$

The edge position $\omega_{\text{max}} \equiv x_0$, $\sigma_x$ and coefficients of the first-order polynomial $p_1(x)$ are the free parameters of the above response function, formula (4), which takes into account the energy spread of backscattered photons due to the energy distribution of the collider beam.

$$f(x) = A \begin{cases} 
\exp \left( -\frac{(x-x_0)^2}{2\sigma^2} \right), & 0 < x - x_0 < +\infty, \\
C + (1-C) \exp \left( -\frac{(x-x_0)^2}{2(K_0\sigma)^2} \right), & -K_0\sigma x < x - x_0 \leq 0, \\
C + (1-C) \exp \left[ \xi \left( \frac{x-x_0}{(K_0\sigma)} + \frac{\xi}{2} \right) \right], & -\infty < x - x_0 \leq -K_0\sigma x,
\end{cases} \quad (10)$$

where $K_0\sigma$ is the deviation of the wider gaussian distribution from $x_0 - \xi(K_0\sigma)$ to $x_0$, and $x_0 - \xi(K_0\sigma)$ is the position where the exponential tail appears. $C$ is responsible for the small angle Compton scattering of $\gamma$ quanta in the passive material between the source and the detector. $\xi$ is the asymmetry parameter.

The calibration procedure is the same as mentioned before. The parameters $x_0$, $\sigma$, $K_0$, $\xi$, $C$ are determined when the calibration peaks are identified and fit.

After calibration, we need to measure the energy position of the sharp edge of the energy spectrum of backscattered photons. The function to fit the edge was obtained in two steps. Firstly, we calculate the convolution of the response function with another Gaussian, which is responsible for the energy spread in the beam:

$$\varepsilon_{\text{nip}}(\text{MeV}) = \varepsilon_{\text{nip}}(\text{MeV}) + 4.75 \cdot 10^{-3} (0.001 \cdot \varepsilon_{\text{nip}}(\text{MeV}))^4. \quad (9)$$
outlet is connected to the HPGe preamp inlet to provide non-linearity and declared by the manufacturer to have 15 ppm integral non-linearity (in 99.5% of scale). A precision pulse generator (BNC model PB-5) is adopted for detailed calibration purposes. 

Between 2 and 6 MeV, there is no source for calibration. To remedy such a defect, besides the radiation sources listed above, a precise pulse generator is used at BEMS commissioning are as follows:

- $^{137}$Cs : $E_{\gamma} = 661.657 \pm 0.003$ keV,
- $^{60}$Co : $E_{\gamma} = 1173.228 \pm 0.003$ keV,
- $^{60}$Co : $E_{\gamma} = 1332.492 \pm 0.004$ keV,
- $^{16}$O$^+$ : $E_{\gamma} = 6129.266 \pm 0.054$ keV.

However, between 2 and 6 MeV, there is no source for calibration. To remedy such a defect, besides the radiation sources listed above, a precise pulse generator is adopted for detailed calibration purposes.

The ORTEC® DSPEC ProTM MCA has a ±250 ppm declared integral non-linearity (in 99.5% of scale). A precision pulse generator (BNC model PB-5) is declared by the manufacturer to have ±15 ppm integral non-linearity and ±10 ppm amplitude jitter. The PB-5 outlet is connected to the HPGe preamp inlet to provide a set of discrete pulse amplitudes, forming a corresponding set of peaks in the measured spectrum. The PB-5 pulse shaping parameters were selected as follows:

- Attenuation: 10,
- Pulse rise time: 50 ns (minimum),
- Pulse width: 14 µs (pulse top: flat),
- Pulse fall time: 500 µs,
- Pulse amplitudes: 0.75, 1.20, 1.40, 1.65, 2.10, 2.50, 2.90, 3.40, 4.00, 4.50, 5.00, 5.40, 6.10, 6.50, 7.00, 8.50, 9.00, 10.0 V, forming 19 calibration peaks;
- Pulse repetition rate: 20–50 Hz.

Switching between the different amplitudes listed above occurs randomly in time via a simple computer script.

To test the calibration effect, two reference lines from $^{232}$Pu $^{13}$C] gamma were used. $\alpha$-decay of $^{232}$Pu provides the reaction:

$$\alpha + ^{13}$C $\rightarrow ^{16}$O$^+$ $. \quad (13)$$

An excited oxygen nucleus emits $\gamma$-rays with energy of $6129.266 \pm 0.054$ keV [29]. The p-type HPGe detector used at BEMS is shielded from neutrons, emitted in reaction (13), by about 10 cm of paraffin. The presence of these neutrons lead to the reaction:

$$n + p \rightarrow d + \gamma \ , \quad (14)$$

from which we can observe 2223 keV $\gamma$-rays as a by-product of such a configuration. This energy can be found in Refs. [30, 31].

Table 1 lists the results of measured energies from $\gamma$-rays and pulse generator. The comparison confirms the reliability of pulse generator calibration.

| energy  | $\gamma$-ray               | pulse generator         | reference       |
|---------|---------------------------|-------------------------|----------------|
| 6129 keV| $6129.451 \pm 0.064$ keV  | $6129.208 \pm 0.062$ keV| $6129.266 \pm 0.054$ keV |
| 2223 keV| $2223.144 \pm 0.272$ keV | $2223.149 \pm 0.022$ keV| $2223.24835 \pm 0.00008$ keV |

6 Laser interlock system

Laser light is invisible, dangerous to people who work in the corridor or tunnel near the NCP of BEPC-II. A laser interlock system is a good way to protect people from laser damage. Only when people evacuate from the BEPC-II storage ring, and the tunnel door is closed, can
the BEMS laser be activated, and an indicator light will be turned on. After the shutter control is switched on, the laser will be emitted.

As mentioned before, the laser is located in the corridor. It could be dangerous to the BEMS staff who enter the corridor, so the door of the corridor is interlocked with the laser. When the corridor door is opened, the laser output will be terminated automatically.

When the moving prism was replaced by the rotary platform, the beam measurement switch between electron and positron became dangerous, because the laser rotated 180 degrees. Once the laser contacts with flammable material, it is likely to cause fire. Therefore, the status of BEMS has to be interlocked with the laser. When the measured beam need to be switched, the laser will be turned off before the rotary platform is rotated.

A main switch was installed near the corridor door. This switch is disconnected during the BEMS instruments test in the corridor. Only when all operations are performed will the main switch be turned on and the laser operate.

7 Upgrade effect

The effect of the upgraded BEMS was checked during the Y(2235) data taken in April 2015. Figure 8 (a) and (b) show the measured Compton edge of the scattered photon energy spectrum with upgraded components for electron and positron separately. It is clear that using twelve minutes’ data collection, the Compton edge is sharp. The fit results are listed in Table 2. The measurement precision of beam energy is about 6.5×10^{-5}, and the energy spread is better than 15%. A beam energy measurement system was built at VEEP-2000 in 2014 [32]. Using the same data taking time, our measurement precision is better than that of VEEP-2000.

![Fig. 8. (color online) The measured edge of the scattered photons energy spectrum. The line is the fit result. (a) Electron case; (b) Positron case.](image)

Table 2. The typical values of beam energy and energy spread after BEMS upgrade.

|          | positron       | electron      |
|----------|----------------|---------------|
| energy/MeV | 1117.134 ± 0.071 | 1116.763 ± 0.039 |
| energy spread/keV | 726.9 ± 102.6   | 741.1 ± 50.6    |

8 Summary

BEMS has greatly increased the measurement capability for both BEPC-II accelerator and BES-III detector, and has become an indispensable part of their running. Many technical details have been provided for clearly understanding the working process of the whole system. The upgrade improvements in particular have been described in detail.

Listed in Table 3 are the main upgraded components of BEMS during the past several years. A more powerful laser and higher transmission rate of ZnSe lenses and viewports will increase the number of photons colliding with beams and shorten the data taking time for measurement at the same accuracy. Because of the use of an electric cooler instead of LN\(_2\), the LN\(_2\) refilling time is no longer needed, and this time is spent on data collection. The new calibration response function for the HPGe detector and fitting function for the energy spectrum will help to get more precise beam energy.

After the above upgrade, BEMS is more efficient, more BES-III running time is spent on data collection, and the time required to determine the beam energy is much shorter. More precise energy measurement results are expected for the forthcoming BES-III analysis.

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Table 3. The detailed upgrade component of BEMS.

| previous system                  | upgraded system             | upgrade time | improvement                                      |
|----------------------------------|------------------------------|--------------|-------------------------------------------------|
| focus lenses ZnSe                | new focus lenses             | 2011.4       | laser transmission rate rise to 98%             |
| no moving shielding              | 10 cm moving shielding       | 2011.9       | higher signal background ratio                  |
| no interlock                     | USB interface relay         | 2012.3       | protect staff from laser                        |
| moving prism                     | rotary platform              | 2012.3       | more durable                                    |
| LN$_2$ cooling                   | electric cooler cooling      | 2013.8       | LN$_2$ refill time is saved                     |
| GaAs viewport                    | ZnSe viewport                | 2014.8       | laser transmission rate rise to 76%             |
| laser with power 25 W            | laser with power 50 W        | 2014.12      | number of laser photons double                  |

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