RECENT DEVELOPMENTS ON BEAM OBSERVATIONS AT SRRC

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Abstract

In this paper, we will present some recent developed methods of beam observations and their experimental results. These methods including: beam energy measurement by laser Compton scattering, investigating electron beam orbit sensitivities on the flux of the photon beam line, beam lifetime investigation in storage rings.

1 INTRODUCTION

We have been trying to utilize the known principles of Beam physics and the existing Photonics knowledge and devices to investigate or to perform new methods of beam observations. In this paper, we will present some recent developed methods of beam observation and their experimental results. These methods including: beam energy measurement by laser Compton scattering, investigating electron beam orbit sensitivities on the flux of the photon beam line, beam lifetime investigation in storage rings. Most of the above mentioned detecting principles and methods are novel approaches. Only brief description and results are presented in this review. References are provided for more detail information for each individual study. All of the experiments are performed on the electron beam in the storage ring of Taiwan Light Source(TLS) of Synchrotron Radiation Research Center(SRRC), Taiwan.

2 BEAM ENERGY MEASUREMENT BY LASER COMPTON SCATTERING[1],[2]

Two conventional approaches of measuring the electron beam energy are to measure the depolarization resonance and measure the magnetic field strength of the bending magnets. The depolarization resonance[3] method has the smallest relative energy uncertainty, e.g., 10^{-5}; however, this method involves the complexity of measuring the electron beam polarization. The relative energy uncertainty of measuring the magnetic field strength is around the order of *0.5%*. In this study, we propose a method capable of providing an intermediate relative energy uncertainty with an easier measurement setup than that of the depolarization resonance method. Here the electron beam energy is measured by using laser Compton scattering. The method, we presented, can be applied to any high energy ($\gamma>>1$) electron beam. The techniques include aligning and focusing for far infrared, synchronously measuring the back-scattered photons, and reducing background radiation from Bremsstrahlung.

The method of Compton scattering to measure the electron beam energy in the storage ring or to produce quasi-monochromatic γ-rays is characterized by excellent signal-to-noise ratio. To acquire a high γ-ray flux, a pulsed CO_2 laser with up to 2.67MW peak power is employed. Owing to the fact that the background radiation from Bremsstrahlung is extremely high (about *1200 counts/sec* at *20mA* electron beam current), how to effectively subtract the background radiation is a relevant concern. In this study, we developed the method of synchronous measurement to resolve the above problem. The synchronous measurement used a gate to periodically allow the signals to pass from the detector to the counting system. Since the scattered photons were produced after the laser pulse reached the interaction region, the laser could provide a trigger signal for the gate to open. The method proposed herein increases the signal to noise ratio from *1.2* to *42.5*. Also, to enhance the collision rate, we have developed a simulation program to optimize the optics system.

The entire experimental system consisted of the optical system, detecting system, and signal processing instruments. The optical system was located inside the radiation shielding wall of the storage ring, while the detecting system and the signal processing instruments were located outside the shielding wall. Fig. 1 presents the entire system's schematic diagram. According to this figure, the laser photons pass through the optical system into the storage ring's straight section. After being scattered by relativistic electrons, the γ-rays passes through the lead collimator and is then detected by the HPGe detector. The signal processing instruments, then, acquire the back-scattered γ-rays' spectrum.

Considering that the highest energy of the back-scattered photons was around *3000keV*, we chose ^{24}Na the standard source in energy calibration of the HPGe detector since the two characteristic energies of ^{24}Na were *1368.4keV* and *2753.6keV*. Those energies contributed to a sum-peak energy of *4122keV* that could be applied to the interpolation method in energy calibration.

Figure 2 presents the spectrum of the Compton scattering with a collimator having an inner diameter of *3mm* that corresponded to a half opening angle of *0.2241mrad*. The background radiation's counting rate without the laser Compton scattering effect was around *0.82 counts/sec* with gating. After the laser collided with the electron beams, the counting rate raised to *34.83 counts/sec*. The *S/N* ratio was approximately *42.5*.

The highest back-scattered γ-ray energy could be estimated from the sharp edge of the spectrum as shown in Fig. 2. For our latest experiment, it was 3054keV±2.6keV. According to the results, we can infer that the electron beam energy was 1.3058±0.0017GeV. The relative energy measurement uncertainty of this experiment is *0.13%.*

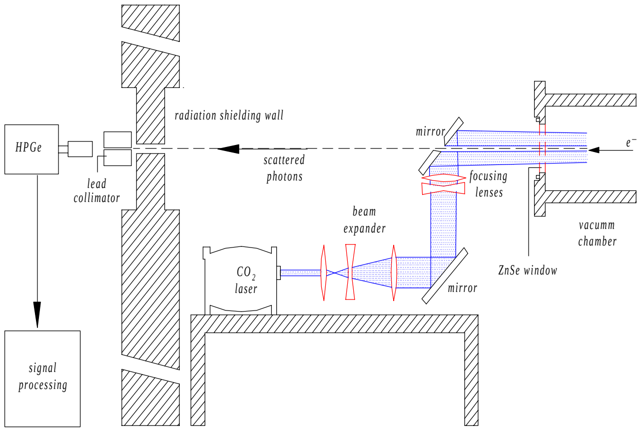

FIG. 1 Schematic diagram of the overall system: part of the vacuum chamber of the storage ring, optical system, detecting system, and signal processing system.

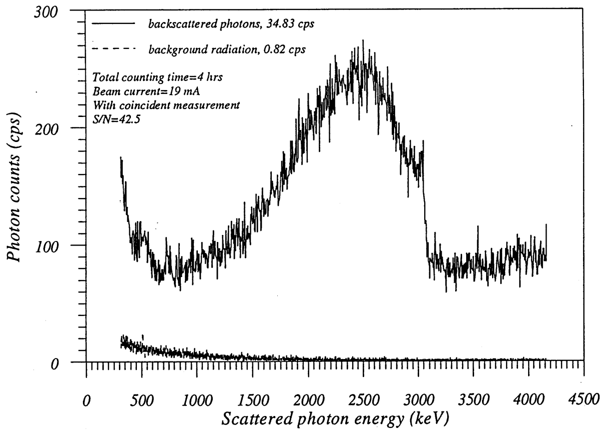

FIG. 2 γ-ray spectrum of Compton scattering with collimator of *3mm* diameter under synchronous measurement. (electron beam current=*19mA*, counting time=*4hrs.*, and *S/N* ratio =*42.5.*)

3 INVESTIGATING ELECTRON BEAM ORBIT SENSITIVITIES ON THE FLUX OF THE PHOTON BEAM LINE[4]

The photon beamline having an extremely high resolution is one of the primary characteristics of a third generation synchrotron radiation light source. Such characteristic has caused the beamlines' optical systems to become quite sensitive to their photon sources' position and angle, i.e. the electron beam orbit. A fundamental issue of all of these light sources, the beamline flux fluctuates due to instabilities of the electron beam position and angle. This study examines the beamline flux sensitivity due to an electron beam's positional and angular changes at the source point of the beamline. The fact that synchrotron radiation sweeps in the horizontal plane, accounts for why the sensitivity of vertical beam displacement is significantly higher than that of horizontal beam displacement. Therefore, the former is addressed herein. Beam experimental and numerical studies have been undertaken. Here we presented the results of the experimental study. It was performed by varying the size of either the electron beam's orbit local position bump or that of the local angular bump. Changes in the beamline flux are measured at the entrance slit downstream. Those two types of local bumps are created by four correction magnets. The strength of four correction magnets must adhere to a certain ratio to control the amplitude and slope of the electron beam's orbit at a given position in a ring. The experiments in this study are conducted on the 6m-HSGM (6 meter High energy Spherical Grating Monochromator)[5] beamline at TLS.

This study, for the first time, experimentally provides a conversion factor of the electron beam's orbit instabilities to the beamline flux fluctuations. This study also provides further insight into the decoupling of the instability sources which may originate from either the accelerators or the beamline systems e.g., vibration of mirrors. Also, with the knowledge of this conversion factor, accelerator physicists can use their own diagnostic devices to investigate the orbit instabilities and subsequently to convert their results into the effects on beamlines. Comparing the beam experimental and numerical results allows us to check the front part of the beamline's optics system. Results obtained from the beamline studied herein indicate that 10 μm vertical beam position displacement causes a relative photon flux change of 0.9±0.3%, as measured at the entrance slit downstream. This observation corresponds to the numerical results. In addition, a vertical beam angular change of 10 μrad causes a relative photon flux change of 1.2±0.4%. The above two values depend on the electron beam size, slit size as well as the beamline's optics. The general requirement of the beamline's relative photon flux fluctuation is around 0.1% to 0.5%[6] for a typical high resolution beamline of a third generation synchrotron radiation light source. Herein, the beam experimental studies, provide a more thorough understanding of the different mechanisms causing the beamline flux to fluctuate by the beam position change and by the beam angular change.

The experiments are performed by varying the size of either the electron beam's orbit local position bump or that of the local angular bump. Changes in the beamline flux are measured at the entrance slit downstream. The photon flux was measured by a photon electric detector located next to the entrance slit. The sensitivity certainly depends on the size of the entrance slit. The slit size was set at 50 μm in all of the experimental and numerical studies presented herein. The electron beam orbit position bump and angular bump were created by using four vertical orbit correction magnets. Therefore, the electron beam position and angle could be independently controlled at the beamline's source point. Figure 3 depicts a typical orbit position bump (upper one) and a typical orbit angular bump (lower one) used in the experiments. The beamline's source point is located at the angular bump's zero-cross point.

The electron beam position and angle at the beamline's source point were calculated by reading two Beam Position Monitor (BPM) values: one upstream and one downstream of the source point. Herein, we demonstrate how they were calculated. The orbit between the two BPMs can be assumed to have been deformed by two dipole errors, which are separated by 90 degrees in betatron phase. By using the two BPM readings and their betatron phases and Twiss parameters as well as the closed-orbit distortion equation,[7] the strength of the assumed dipole errors can be obtained. The orbit position at the beamline's source point can be identified by again applying above results to the closed-orbit distortion equation by knowing the betatron phase and Twiss parameters of the source point. The orbit slope at the source point can be derived by the same method.

For the case involving the position bump in each step, about 20 to 40 μm of the beam position at the source point was varied. For the case involving the angular bump in each step, about 20 to 40 μrad of the beam angle at the source point was varied. We began with a reasonably good orbit i.e. the rms. of the vertical displacements less than 200 μm. The angle of the Vertical Focusing Mirror (VFM) was then adjusted until obtaining the maximum photon flux. This adjustment ensured that the focused photon beam's center pass through the center of the entrance slit. After each step of either the position bump or angular bump variations, the change in photon flux was recorded ; the VFM was then readjusted until obtaining the maximum photon flux again. Then, the next step of variation was proceeded with. This procedure would ensure that the results obtained herein would not depend on special initial conditions (i.e., the initial beam orbit). Gaining the maximum photon flux by adjusting the VFM's angle is a routine fine tuning done by the beamline user after every injection.

Figure 4 presents the measurement results for which only the position bump was varied. Horizontal axis denotes the beam position at the source point. The left vertical axis represents the relative photon flux fluctuation ($\Delta I_o/I_o$) per unit beam position displacement at the source point. While varying the beam positions, the beam angle should remain unchanged. Due to the position bump's imperfection, the beam angle at the source point slightly changes. This figure also plots the beam angle's value at each step on the right vertical axis, i.e. the X-X' correlation.

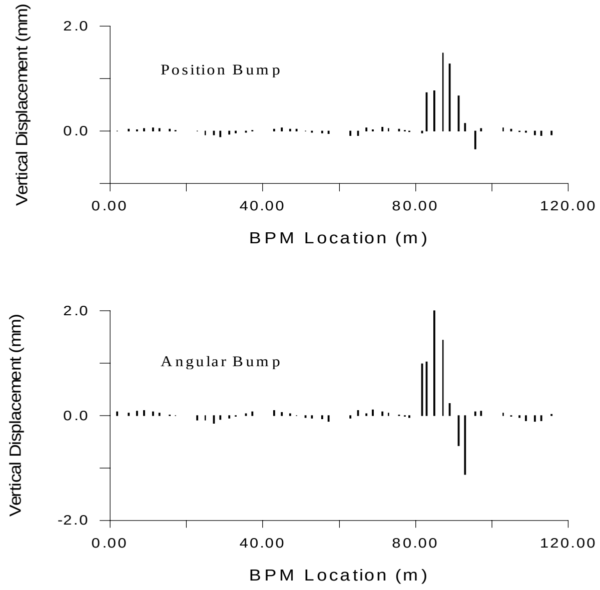

Fig. 3 A typical orbit position bump (upper one) and a typical orbit angular bump (lower one).

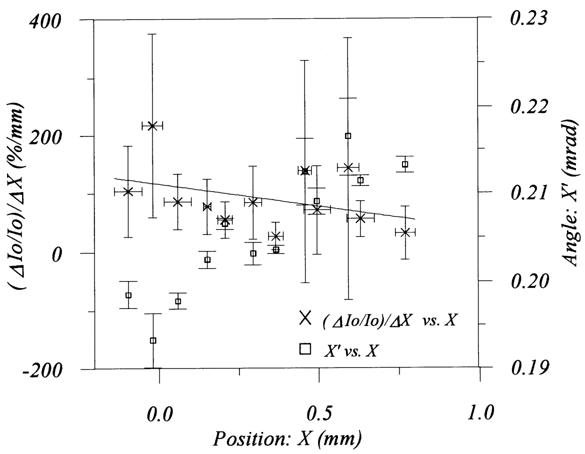

Fig. 4 The measurement results for which only the position bump was varied.

The angular bump study results as mentioned before (not presented in detail in this review) clearly imply that the effects due to the beam angle changes in those sizes (with most of them less than 5 μrad between each step) can be neglected as compared to the effect caused by a 20 to 40 μm change per step. Therefore, from this figure, we can infer that 10 μm vertical beam position displacement causes a relative photon flux change of 0.9±0.3%.

4 BEAM LIFETIME INVESTIGATION IN STORAGE RINGS[8]

For an electron storage ring not encountering vital instabilities, the dominant beam lifetime effects are typically the gas scattering effects and the Touschek effect. Therefore, a thorough understanding of the relative beam lifetime contributions from the Touschek effect and from the gas scattering effects is critical for developing strategies to lengthen the beam lifetime. For example, if the beam lifetime is dominated by the Touschek effect, the lifetime should be increased by increasing the RF voltage, increasing the physical or dynamic apertures, or decreasing the beam density by increasing the beam volume. However, if the gas scattering effects dominate the beam lifetime, the lifetime should be increased by improving the vacuum condition and/or eliminating the ions trapped by a negatively charged stored beam. As is generally known, the two unequal bunches method[9] can separate the beam lifetime contributions from these two effects. However, what the method measured was basically the lifetimes of the few bunches mode. In a multibunch operation, owing to the growth in the beam size/length possibly caused by the couple bunch effects, the Touschek lifetime can differ significantly from that of the few bunches' case. Also, the ion effects normally do not appear if measured by the two unequal bunches method. Therefore, we present a method, where we fill every bucket and then measure the beam lifetimes before and after enlarging the transverse beam sizes. Such an enlargement can be achieved by driving the beam into the difference resonance. Using this method, we measure the lifetimes comprised of two different Touschek lifetimes with the same gas scattering lifetime. This allows us to estimate the Touschek lifetime and the gas scattering lifetime, including the ion effects (if they exist). The ion effects normally do not appear if measured by the two unequal bunches method.

The two unequal bunches method was performed by filling two bunches in opposite buckets in the ring. One bunch had a larger current than the other one. Since we know that the Touschek effect depends on the bunch's particle density, if the two bunches have the same bunch volume, they will have different particle densities and different Touschek lifetimes. The assumption of the equal bunch volume is adequate as long as the current of each bunch is below the threshold current of the microwave instability and the potential well distortion can be neglected. The threshold current of the microwave instability of the TLS's storage ring was measured to be above 3 mA. In all the experiments performed by this method, the larger bunch current is always below 3 mA. According to the bunch length measurement of this machine, the potential well distortion is negligible for a 3 mA beam current with a 700 kV RF voltage. The lifetime due to the gas scattering effects depends on the vacuum of the storage ring which is the same for the two bunches. By measuring the beam lifetime of the individual bunch and subtracting the effects of gas scattering, which are the same for both the bunches, we can obtain the beam loss rate of the Touschek effect. The gas scattering lifetime can be derived by subtracting the Touschek lifetime from the total lifetime of the individual bunch.

The beam current vs. time for each individual bunch was measured by the voltage signal of a broad band pickup. The lifetime of each individual bunch was then calculated. The calibration of the broad band pickup signal was done by a DC current transformer (DCCT) when a single bunch beam was stored. Figure 5 summarizes these results. The horizontal axis is the difference between the two bunch currents in mA. The vertical axis is the difference of the inverse of the bunch total lifetime. From the slope of the fitted line, the proportionality constant A can be obtained and the Touschek lifetime for a given bunch current can be calculated. Under the experimental conditions of the nominal transverse beam sizes (σ_x = 180±9 μm, σ_y = 70±5 μm), a total RF voltage of 700 kV and a bunch length of 100 ps, the results derived from Fig. 5 are:

Touschek lifetime(min)=(366±52)/(single bunch current in mA)

In the following calculations, the above results are used to estimate the multibunch beam lifetimes. For a total beam current of 195 mA (filling 140 bunches), the single bunch current is 1.39 mA. The Touschek lifetime is 263±38 min. The measured total beam lifetime at 195 mA with a multibunch mode by DCCT is 238±1 min. Subtracting 1/(263 min) from 1/(238 min) yields the gas scattering lifetime as 2500±1361 min. The reason of the large uncertainty was discussed in Ref[8].

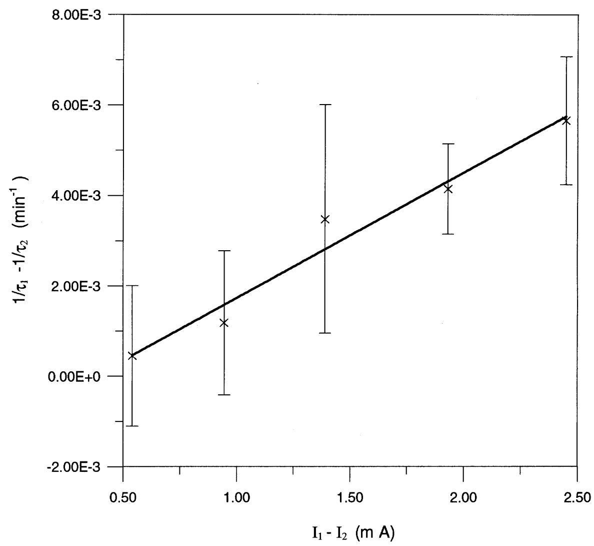

Fig. 5 The Touschek lifetime measurement by the two unequal bunch beam method. The horizontal axis is the difference between the two bunch currents in units of mA. The vertical axis is the difference of the inverse of the bunch total lifetime.

In the multibunch method, using the same total RF voltage, we first measured the total beam lifetime at the multibunch mode with the nominal transverse beam sizes (σ_x = 180±9 μm, σ_y = 70±5 μm). The beam current was 195 mA (filling 140 bunches) with a total beam lifetime τ_a of 238±1 min. Next, the beam was driven into the difference resonance and the transverse beam area (σ_x =

357±14 μm, σ_y = 353±16 μm) was increased by a factor of 10. The beam current was 194.3 mA with a total beam lifetime τ_{10a} of 960±1 min. If the difference between the beam current of 195 mA and 194.3 mA can be disregarded, the following two equations can be solved easily, yielding a Touschek lifetime τ_T of 285±14 min and a gas scattering lifetime τ_{gas} of 1443±280 min which includes the ion effects, if they exist.

$$1/\tau_a = 1/238 = 1/\tau_T + 1/\tau_{gas} \quad (1)$$

$$1/\tau_{10a} = 1/960 = 1/(10\tau_T) + 1/\tau_{gas} \quad (2)$$

The results obtained above are valid for estimating the beam lifetimes for the multibunch operation mode because all the measurements are taken in the multibunch mode.

According to the measurement results, the Touschek lifetime is longer when measured by the multibunch method (285±14 min) than when measured by the two unequal bunches method (263±38 min). The reason for this discrepancy is that in the two unequal bunches method, the Touschek lifetime was measured at the few bunches mode and in that mode, the bunch lengthening effects, possibly caused by the couple bunch effects may not be as prevalent as those in the multibunch mode. For the estimation of the gas scattering lifetime of the operation mode i.e., the multibunch mode, in which the total lifetime was measured, we used the Touschek lifetime measured at the few bunches mode. This misuse caused the Touschek effect in the multibunch mode to be overestimated and consequently, underestimated the gas scattering effects in the multibunch mode. The Touschek lifetime is longer by 8% {i.e., (285-263)/[(285+263)/2] } when measured by the multibunch method than when measured by the two unequal bunches method. The theoretical value of the Touschek lifetime at the corresponding parameters is 302 min. There is a 54% {i.e., (2500-1443)/[(2500+1443)/2] } discrepancy of the gas scattering lifetime measured by the two methods. Besides the consequence of the overestimation of the Touschek effect as previously mentioned, a significant reason for this discrepancy is a possibility of the discounting of the effects of any trapped ions in the multibunch operation mode, when the lifetimes were estimated by the results of the two unequal bunches method. The effects of the trapped ions causes the scattering between the beam and the ions which is considered a part of the gas scattering effects. Such a possibility is due to the fact that only two bunches were filled ; one or two large gaps within the beam population could be found in the storage ring. The linear ion trapping theory[10] estimated that fewer ions would be trapped. However, according to the linear ion trapping theory, the larger the transverse beam size the smaller the mass-to-charge ratio of the ions will be trapped. Therefore, we should be conscious that the difference in the vertical beam size used in the multibunch method, will cause the variation of the constitution of the trapped ions. The quantum lifetime (larger than 50 h in the machine under study) due to the physical or dynamic aperture is much larger than the two lifetimes we are studying. Therefore, enlarging the beam size by a factor of 10 does not have any obvious effects on the quantum lifetime. The effect of the dynamic aperture in this experiment is the setting of the energy acceptance through the coupling of the horizontal dispersion. It is a part of the Touschek effect. For different machines, the energy acceptance may depend on the physical aperture or the RF acceptance.

5 ACKNOWLEDGMENTS

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