Review of Transverse Beam Profile Measurements Using Synchrotron Radiation

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Abstract –*Synchrotron radiation (SR) is a tool for non-destructive beam diagnostics since its characters are substantially related to those of the source beam. The spectrum of SR is extremely intense and extends over a broad energy range from the infrared through the visible and ultraviolet, into the soft and hard X-ray regions of the electromagnetic spectrum. The visible light (400 – 800 nm) and X-ray (0.05 – 0.3 nm) regions are used in the beam instrumentation. In the visible light region, transverse beam profile or size diagnostics can be done by an interferometer (light is observed as a wave). Meanwhile, in the submicron beam size measurements, the X-ray SR monitor is commonly used. This paper reports the review of transverse beam profile measurements using SR covering principles and practical experiences with the technique at some accelerator facilities such as Photon Factory, Diamond Light Source, CesrTA, and SuperKEKB.*

Key words: *accelerator, beam instrumentation, transverse beam profile, synchrotron radiation, X-ray, visible light*

I. INTRODUCTION

Beam instrumentation in the accelerator is the 'eyes' of the machine operators, its entail the design, construction and operation of instruments to observe particle beams, and also the research and development to find new or improve existing technique to fulfill particularly new requirements. Beam instrumentation and diagnostics combine the disciplines of accelerator physics with mechanical, electronics, and software engineering, making it a fascinating field in which to work. Several beam parameters that we need to measure in the accelerator (*i.e*. circular accelerator and collider) are beam position (to know the horizontal and vertical positions of the beam throughout the accelerator chamber), beam intensity, and lifetime measurement. Other parameters are beam loss, beam profile (shape of the beam, both transverse and longitudinal planes), and collision rate to measure of how well the beams overlap at the collision point (in accelerator collider) [1].

Nowadays, Synchrotron Radiation (SR) is widely produced by the use of dedicated synchrotron and is employed in applications, ranging from solid-state physics to medicine. More related to this paper, SR results as a powerful tool for non-invasive beam diagnostics and a valuable tool for accelerator operation. This paper will start with reviews of beam instrumentation based on the SR, either visible light or X-ray regions. Finally, there will be a discussion of experiences at Photon Factory, Diamond Light Source, CesrTA, and SuperKEKB, then a summary.

II. SYNCHROTRON RADIATION

Synchrotron radiation has been investigated theoretically for over a century. The fundamental theoretical considerations and investigations of the radiation emitted by the relativistic charged particles in circular motion goes back to the work of Liénard (1898) followed by Schott (1933), Ivanenko and Pomeranchuk (1944), Schwinger (1945), and others; but the first observation - literally, since it was visible light that was generated - came at the General Electric Research Laboratory in Schenectady, New York, on April 24, 1947 [2]. In the circular accelerator (*i.e*. storage ring), there are three kinds of SR sources: bending magnets (BM), wigglers, and undulators. One of the bending magnets of the INFN-LNF DAΦFNE storage ring as a source of the synchrotron radiation is shown in Fig.1.

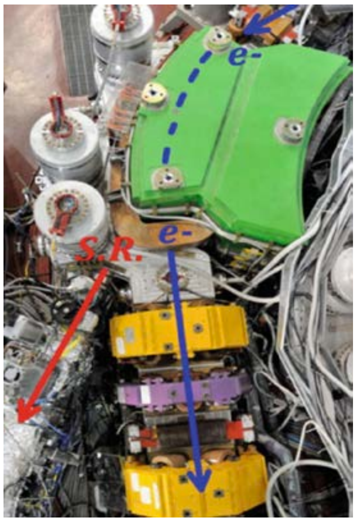

Fig 1. The electron moving at relativistic speeds are forced by magnetic fields to follow curved trajectories in which they emit electromagnetic radiation in the direction of their motion, known as synchrotron radiation. One of the bending magnets of the INFN-LNF DAΦFNE storage ring and the initial part of a beamline collecting synchrotron radiation (*courtesy of V. Tullio*)[3].

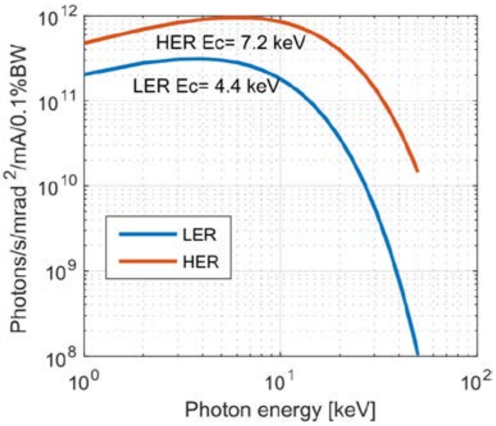

Fig 2. The spectral distribution of synchrotron radiation from bending magnets in SuperKEKB rings. The critical energies are 4.4 and 7.2 keV for Low Energy Ring (LER) and High Energy Ring (HER), respectively. The critical energy corresponds to critical frequency ω_c and divides the spectrum into two parts of equal radiated power: 50% of the total power is radiated at frequencies lower than ω_c and 50% is radiated at frequencies higher than ω_c.

The properties of the SR are the high intensity emitted radiation, broad and continuous spectral range from X-ray to the infrared region, and natural narrow angular collimation. The spectral distribution of SR from BM in the SuperKEKB accelerator rings is shown in Fig.2.

III. BEAM INSTRUMENTATION BASED ON SYNCHROTRON RADIATION

The beam instrumentation based on SR means measure the fundamental parameters of accelerator through the transverse and longitudinal profiles, size, *etc*., statistically, or dynamically using optical techniques with the synchrotron radiation. The spectrum of synchrotron radiation is extremely intense and extends over a broad energy range from the infrared through the visible and ultraviolet, into the soft and hard X-ray regions of the electromagnetic spectrum. The visible light (400 – 800 nm) and X-ray (0.05 – 0.3 nm) regions are used in the beam instrumentation, while the VUV (vacuum ultra-violet) is not used because of difficulty in actual handling [4].

A. Visible-light Synchrotron Radiation

Transverse beam profile or size diagnostics can be done by simply observing the beam inside of accelerator with a telescope (light is observed as photon) or interferometer (light is observed as a wave). The interferometry instrument is a wavefront-division type of two-beam interferometer using polarized quasi-monochromator light. The SR interferometer uses a double slit to sample the incoming wavefront and obtain the interference pattern along the vertical or horizontal axis with the schematic as shown in Fig. 3.

We can also measure the RMS beam size from one data of visibility, which is measured at a fixed separation of double slit. The RMS beam size σ_{beam} is given by [5]

$$\sigma_{\mathrm{beam}} = \frac{\lambda F}{\pi D}\sqrt{\frac{1}{2}\ln\left(\frac{1}{\gamma}\right)}, \qquad (1)$$

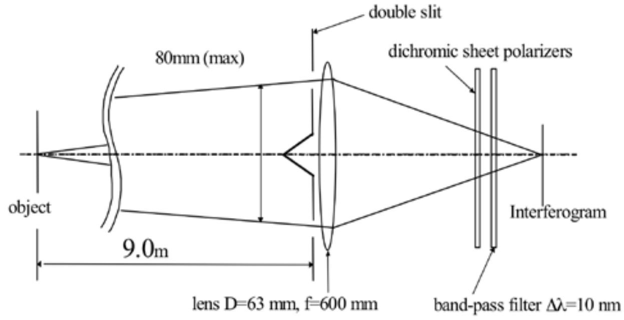

Fig 3. Schematic of SR interferometry at Photon Factory, KEK [5].

where F is distance from source to mirror and γ denotes the visibility, which is measured at a double slit separation of D.

B. X-ray Synchrotron Radiation

In the submicron beam size measurements, the X-ray SR monitor is commonly used. One obstacle to using the information carried by X-rays is the difficulty in imaging them. In contrast to ordinary light, the X-ray cannot be reflected promptly by mirrors or bent by lenses. An instrument that can be used is the single-pinhole camera, which consists only of a small hole in an otherwise opaque material through which an image is projected onto a piece of film. An image is formed because the small hole limits the view of any point onto the film to only one small part of the emitting source.

However, there are conflicting requirements for imaging with a single-pinhole camera. The hole should be small to provide resolution. However, a small hole often has an insufficient area to collect enough X-rays to produce an interpretable picture. This conflict between needing a small hole to obtain resolution and needing a large hole to obtain a sharp X-ray signal often limits the usefulness of the obtainable X-ray pinhole pictures. It is at this point that the capabilities of coded aperture imaging become useful [6]. The coded aperture imaging uses an array of pinholes or slits to achieve large open apertures, which provide improved photon collection efficiency over single pinholes or slits. Recently, the coded aperture imaging is being developed in some accelerator facilities that will be discussed in the Section IV.

IV. EXPERIENCES AT ACCELERATORS

In this section it will be discussed experiences applying beam instrumentation based on visible-light SR interferometer and X-ray at 4 machines: Photon Factory, Diamond Light Source, CesrTA, and SuperKEKB. All four machines are low-emittance electron and/or positron rings, with beam energies ranging from 1.3 to 7 GeV.

A. Experience at Photon Factory KEK

The 2.5 GeV photon factory (PF) ring is the first synchrotron light source which produces the X-ray regions in Japan and has continued in operation for about thirty years. The PF has more than 3000 SR users with around 800 experiment proposals per year [7]. There are several beamlines around the elliptically-shaped storage ring accelerator. The vertical and horizontal beam sizes of the low emittance configuration of the PF were measured via SR interferometer with the schematic as shown in Fig. 3[8]. The two results of the spatial coherence measured at wavelengths of 500 nm and 633 nm are agreed to each other. The vertical and horizontal measured beam sizes were 87.3 μm and 261.2 μm, respectively. While, the vertical and horizontal estimated beam sizes were 110 μm and 263 μm, respectively. In order to reduce the vertical beam size further, the x-y coupling has been corrected using many skew-quadrupoles [9]. As a result, the vertical beam size would be reduced to about 60% of the uncorrected one. This correction has been used since January, 1999.

B. Experience at Diamond Light Source

Diamond Light Source (DLS) is a third-generation light source in Oxfordshire, UK with the bird's eye view as shown in Fig. 4. It has a beam energy of 3 GeV with the first experimental users arrived in January 2007. Optical diagnostics in DLS performed in the X-ray and in the visible domains [10]. In the X-ray domain, two pinhole camera systems provided the transverse horizontal and vertical sizes of the beam. In the visible domain, a CCD camera, a streak camera, and multichannel analyzer provided static and dynamical information of the beam.

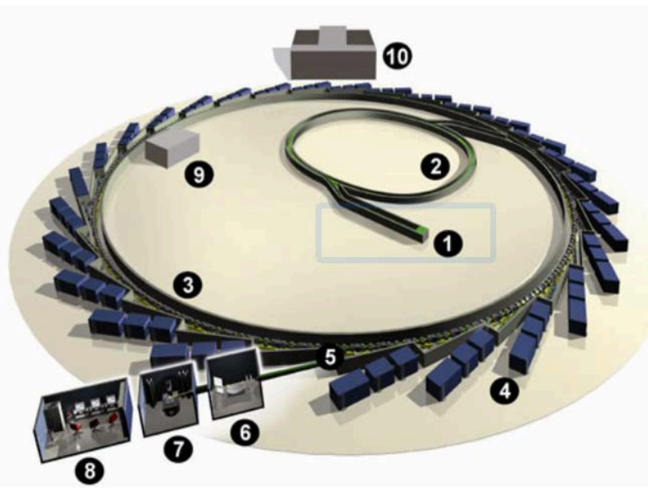

Fig 4. The bird's eye view of the DLS, consists of: (1) Injection system, (2) Booster synchrotron, (3) Storage ring, (4) Beamlines, (5) Fronts end, (6) Optics hutch, (7) Experimental hutch, and (8) Control cabin [11].

Pinhole camera system

The X-ray pinhole camera is composed of a source, a pinhole, and a screen to image the source, as described in Fig. 5. The X-ray beam from the bending magnet goes

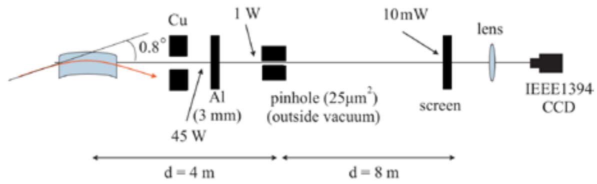

Fig. 5. Schematic of the pinhole camera system for measuring the electron beam transverse profile in the Diamond Light Source [12].

through the beam port absorber. The absorber is a copper block, to absorb the totality of the X-ray beam, then the beam passes through an aluminum window.

The spatial resolution of an imaging system may be described by the point spread function (PSF). The image formed on the camera is the convolution of the source profile, and of the PSF of the diffraction through the pinhole, and of the PSF of the x-ray camera. Consequently, the convolved PSF of the diffraction and of the camera determines the smallest image size measurable by the imaging system. In 2010 [13] the point spread function of several scintillator screens (P43, $CdWO_4$, and LuAG) is measured, and it shows that the contribution of the diffraction and the screen point spread functions have to be considered for accurate measurements. It showed measurements of the vertical beam sizes as small as 6 μm.

Coded aperture (CA) imaging system

In 2013, a high-energy coded-aperture chip was installed in the X-ray beam diagnostic line. The coded aperture imaging uses an array of pinholes or slits to achieve large open apertures, which provides improved photon collection efficiency and resolution over single pinholes. A study was then performed varying the beam size and comparing measurements made with the CA and with the pre-existing single-slit aperture [14]. Results showed good correlation between the coded aperture and the pinhole measurements, though with a small systematic difference in measured sizes.

C. Experience at CESR Test Accelerator

Cornell Electron/Positron Storage Ring (CESR) test accelerator is the collaboration group to investigate the physics of ultra-low emittance beams of electrons and positronslocated at Cornell University in Ithaca, NY, USA.

Visible light beam size monitor

A beam profile monitor utilizing visible SR from bending magnet has been designed and installed in CESR [15]. The monitor employs a double-slit interferometer to measure both the horizontal and vertical beam sizes over a wide range of beam currents. By varying the separation of the slits, beam sizes ranging from 50 to 500 µm can be measured with a resolution of approximately 5 µm.

X-ray beam size monitor (xBSM)

The X-ray beam size monitor (xBSM) is an instrument for measuring the sizes of the electron and positron beams using synchrotron radiation in CESR. Single-shot measurements were carried out with majority of experiments at 2 GeV [16,17], with some at 4 GeV [18]. The detector was a 32-pixel InGaAs detector with 50 µm pitch, and the optics chips used were generally made of 0.5 µm Au on 2.5 µm Si substrate. In addition, there was a single-slit aperture made of tungsten. Two types of coded aperture were used, both CAs showed better single-shot resolutions than the single-slit at the smallest beam sizes, with the second CA design outperforming the first between 10 and 50 µm at 2 GeV [16].

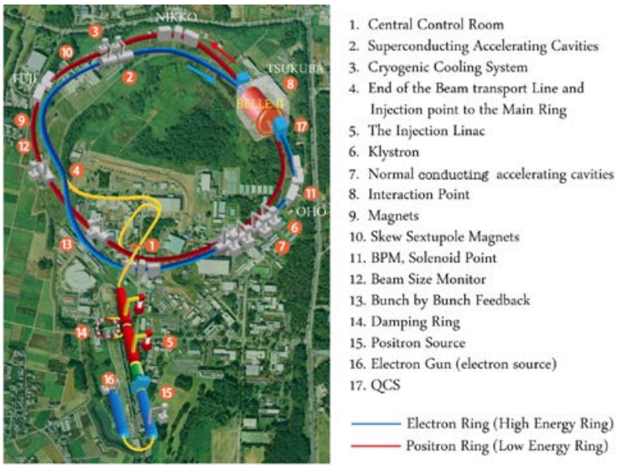

Fig 6. Facilities and components of the SuperKEKB accelerator facility. Ring's circumference is ~3 km with four experimental hall buildings (Fuji, Nikko, Tsukuba, and Oho)[19].

D. Experience at SuperKEKB

The SuperKEKB accelerator is a double-ring collider with asymmetric energy: the positron beam energy (Low Energy Ring, LER) is 4 GeV, and the electron beam were designed for each ring: a single slit mask, a multi-slit CA mask, and a URA CA mask [21]. Fig. 8 shows the patterns of all optical elements, the black color indicates energy (High Energy Ring, HER) is 7 GeV. It is an extensive up-grade to the KEKB B Factory collider. The layout of the SuperKEKB is shown in Fig. 6.

When the LER and HER beams achieve their targeted emittances the vertical beam sizes at the monitor source points are less than 18 µm in both rings. For a 400 nm measurement wavelength, the SR interferometer would be necessary to be able to measure visibilities of around 98% to measure the vertical beam sizes at the source points, which is extremely challenging [20]. In the horizontal direction, the beam sizes are 10 times (or more) larger than those in the vertical direction, so the required measurable maximum visibility is more reasonable than in the vertical direction (around 90%). Furthermore, the SR interferometer will not be adequate for single-shot (bunch-by-bunch, turn-by-turn) measurements, which are useful for studying beam instabilities, because of limited photon statistics at short integration times. Accordingly, there are two types of SR monitor on each SuperKEKB ring: visible SR interferometers, primarily used for horizontal beam size (XRM) have been installed and commissioned at both measurements, and X-ray monitor, primarily used for the vertical beam size measurements. The X-ray monitors rings, meanwhile the SR interferometer status is under construction.

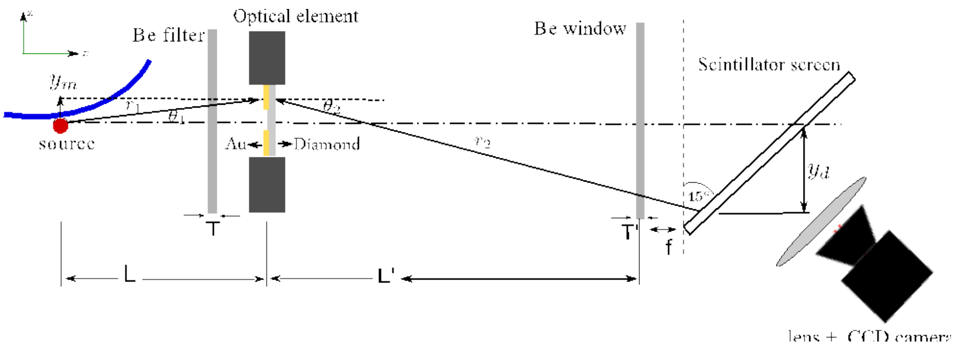

Fig 7. Schematic of the XRM beamline at each ring (not to scale). Each XRM consists of a beryllium filter placed upstream of the optics to reduce the heat load, three sets of optical elements (a single pinhole and two sets of coded apertures), a beryllium window, and a 141-µm-thick scintillator with a CCD camera focused on the scintillator as an imaging system. The scintillator screen is tilted 45° in the horizontal plane, so that the camera and lens are out of the way beam.

X-ray beam size monitor (XRM)

The schematic of XRM is shown in Fig. 7. Phase 1 of SuperKEKB commissioning occurred in spring of 2016, with Phase 2 in spring of 2018. Phase 3 is planned for Spring of 2019. Three sets of optics chips, made of 18 microns of Au on a 600-micron CVD diamond substrate,

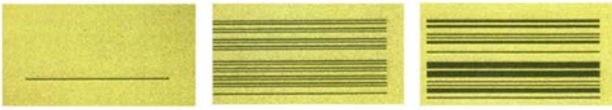

Fig. 8. Mask pattern (a) pinhole, (b) 17 multi-slits, and (c) 12-slits URA for both rings. The mask consists of 20-μm-thick gold masking material on 600-m-thick diamond substrates.

the hole/slit, meanwhile, the transparent (*i.e*.,yellow color for this case) indicates the mask/gold. After passing through an optical element, the X-rays from a point source form a diffraction pattern with peaks on the detector depending on the pattern of the optical element. The design concept and procedure have been explained in the previous publication [22].

Commissioning

In Phase 1 of SuperKEKB commissioning, the online vertical beam size measurement system based on template fitting was implemented, and extensive calibration checks were carried out [22, 23]. In addition, electron-cloud blow-up studies were carried out in the LER [24], which involved measuring the beam size as the beam current was gradually increased, with beam blow-up due to electron-cloud-induced head-tail instability setting in above about 500 mA. Beam sizes from about 35 microns at currents below the blow-up threshold, and 250 microns at 850 mA, were observed. Very good fill-to-fill agreement between the single-slit, multi-slit and URA mask measurements was found, especially below 150 microns. Emittance measurements were carried out in both rings, and compared to estimates made by the beam optics group [23].

In the LER, good agreement between measured and expected beam sizes was found, while in the HER, a large systematic smearing term was found that led to excessively large measured beam sizes as compared to the optics model. This was attributed to scattering due to an excessively thick Be filter upstream of the HER optics chips. For Phase 2, this filter was made much thinner (and the LER filter made thinner as well); measurements of the smearing in Phase 2 showed that it had been reduced to levels small enough that the smallest possible beam sizes in both rings should be measurable with the current system. Emittance measurements made in Phase 2 also agreed with the optics group's models, in both rings.

V. SUMMARY

In the beam instrumentation based on synchrotron radiation, the visible light (400 – 800 nm) and X-ray (0.05 – 0.3 nm) regions are commonly used. In the visible light region, transverse beam profile or size diagnostics can be done by an interferometer. Meanwhile, in the submicron beam size measurements, the X-ray SR monitor is commonly used. Those techniques have been tested for beam size measurements at Photon Factory, Diamond Light Source, CesrTA, and SuperKEKB, and gave reasonable results. These results show that the synchrotron radiation is a promising tool for non-destructive beam diagnostics. The research and development into X-ray SR monitor for beam size measurement is underway in many facilities (*e.g*. CesrTA, Diamond Light Source, and SuperKEKB) with improvement in the optical elements and detector read-out system in order to get better resolution.

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