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Transverse beam profile measurement system for the Duke storage ring

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ABSTRACT

The transverse beam emittance is a crucial parameter determining the brightness of an electron storage ring based synchrotron radiation source. The beam emittance is typically determined using the transverse electron beam size and the beta function at a particular location. For a low energy storage ring, the direct imaging method using visible/UV light has many advantages, including being simple, straightforward, and cost-effective. The resolution of such a system can be quite adequate for measuring electron beams with a reasonably large transverse beam size. In this work, we present the development of a new transverse beam profile measurement system for the Duke storage ring. This new system has been characterized to allow absolute measurements of the electron beam size while achieving better system resolution than previously thought possible for the direct imaging technique. The preliminary measurement results show that this system is capable of measuring the horizontal beam size over a wide range of the electron beam energies and currents. The system has also been demonstrated as a useful tool to study the intra-beam scattering related emittance increase in the storage ring.

1. Introduction

The transverse beam emittance is a crucial parameter for the brightness of an electron storage ring based synchrotron radiation source. The beam emittance is typically determined using the transverse electron beam size and the beta function at a particular location [1,2]. To measure the beam size, synchrotron radiation (SR) is commonly used due to its non-invasive nature. Several techniques to measure the beam size were developed for a variety of storage rings [3–6], such as imaging using an X-ray pinhole camera, SR interferometry imaging using visible light, and direct imaging using the visible/UV spectrum of SR. Using the short wavelength light (X-ray), X-ray pinhole imaging can achieve good resolution [7,8], but at a high cost. Utilizing spatial coherence of synchrotron radiation, the SR interferometry imaging can have even better resolution [9,10], but this method only provides indirect measurements with a relatively complex setup. For a storage ring with a low electron beam energy (typically less than 1 GeV), X-ray pinhole technique is not applicable due to the lack of substantial X-ray radiation from the dipole magnet. In order to measure electron beam size, the imaging technique using visible/UV light is the only direct method for a low energy electron storage ring, and it has an advantage of being simple, straightforward, and cost-effective.

The resolution of such a system is mainly limited by the diffraction effect of the light. By implementing procedures to minimize various contributing factors to the system resolution, e.g. optimizing the aperture size, systematically determining the focal point location and calibrating the focal length of the lens, we have developed a new direct imaging beam profile measurement system with a resolution about 30 μm in the horizontal direction. In the vertical direction, the resolution of the measurement system is limited by both the aperture and the natural opening angle of the synchrotron radiation. For example, for a 1 GeV electron beam in a 1.6 T magnetic field, the vertical root-mean-square (rms) opening angle of its synchrotron radiation is about 2.5 mrad in the visible and UV light region. Using a vertical aperture whose opening angle is larger than this natural opening angle will not help to improve the system resolution that is contributed from the diffraction effect. When optimized such a system can be quite adequate for measuring the horizontal beam size of the electron beam in many low energy storage rings [11–13], including the Duke storage ring.

The Duke storage ring is a dedicated electron beam driver for the Duke Free-Electron Lasers (FELs) [14] and the High Intensity Gamma-ray Source (HIGS) [15]. With great flexibility in energy tuning from 240 MeV to 1.2 GeV [16], the Duke storage ring provides a high-quality, low-emittance electron beam (18 nm rad at 1 GeV [17]) for a variety of scientific research programs [18–22]. In the Duke storage ring, the transverse profile of the electron beam was measured using the SR imaging method. Developed in the early days of the storage ring project, this low-cost measurement system was not fully characterized nor optimized. For example, it utilized the visible spectrum of the SR from a dipole magnet, employed a simple round aperture without a reading scale, and used an uncalibrated focusing lens, which resulted in

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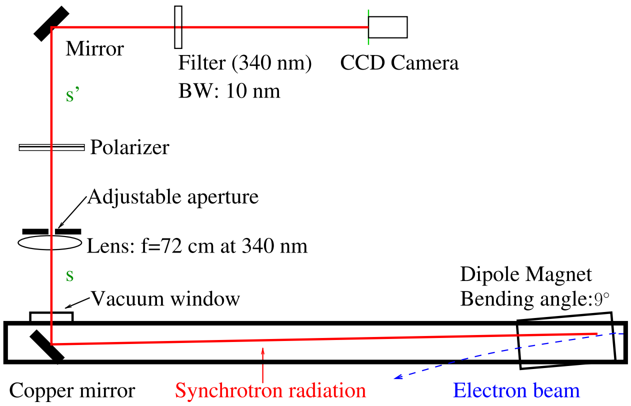

Fig. 1. The schematic of the transverse beam profile measurement system. The direction of the synchrotron radiation is shown as a solid line (red), and electron beam traverses a 9° dipole magnet along the dashed line (blue). The distance from the center of the lens to the sensor of the CCD camera is denoted as s' and the distance from the source point of the light to the center of the lens is denoted as s.

a large uncertainty in the system's overall magnification. While being useful in measuring the electron beam emittance at higher energies (as firstly demonstrated by measuring the electron beam emittance at 1 GeV [23]), the spatial resolution of this system was rather limited due to the lack of optimization.

Based upon the same physical principles, we have recently developed a new transverse beam profile measurement system to significantly improve the system resolution and accuracy. We have chosen to use the narrow band UV (around 340 nm) light for this measurement system. Compared to the commonly used visible light, using the UV light reduces the diffraction effects of the optical system, which helps improve the system resolution. Meanwhile, the conventional optics still can be used. This new system has been used successfully in measuring the horizontal beam size of the electron beam over a wide range of the electron energies and beam currents. The results of the system development and preliminary beam size measurements are reported in this work.

In the following sections, we first describe the overall setup of the beam profile measurement system and the related calibration of several critical components in the system (see Section 2). In Section 3, we report the development to optimize the performance of the system, in particular, the choice of an appropriate aperture size to minimize the diffraction effect in the horizontal direction. In this section, we also discuss the limitation of the system when used to measure the much smaller vertical beam size. In Section 4, preliminary results of horizontal beam size measurements are described.

2. Characterization of the system

In this section, we will first describe the overall layout of the transverse beam profile measurement system, followed by reporting the detailed characterization results of two critical components of the system: (1) the focal lens and (2) the CCD camera.

2.1. Transverse beam profile measurement system

The transverse beam profile measurement system is installed in the west arc of the storage ring to use the synchrotron radiation from its first bending magnet as shown in Fig. 1. SR from the middle of the 9° dipole magnet is extracted through a vacuum window after being reflected by an in-vacuum copper mirror. The extracted light is focused by a lens and then reflected by a mirror to a charge coupled device (CCD) camera located at the image plane of the lens. Several additional elements are used to manipulate the light to improve the system performance, including a rectangular aperture, a linear polarizer filter, and a bandpass filter.

The synchrotron radiation from the dipole magnet contains light of both horizontal and vertical polarization components with the vertically polarized light distributed out of the horizontal plane. The linear polarizer filter is used to filter out the light in vertical polarization to increase the spatial resolution of the system [24]. Improving the performance of the system is achieved by minimizing the diffraction effect. This is done by using a narrow UV bandpass filter to pass through 340 nm light (full width half maximum $\Delta\lambda$ = 10 nm), the shortest wavelength, which can be easily handled using conventional optics. The impact of diffraction effects is also minimized by choosing an optimum aperture size as described in Section 3.

To realize good system performance, the beam image needs to be properly matched to the CCD sensor. The beam size matching needs to take into account of a large range of beam size variations for measuring the electron beam at different energies and with different beam currents. A simple optical system using a single lens (Fig. 1) creates some challenges, especially for a compact setup in which the CCD camera cannot be placed very far away. A reasonable solution is found to use an uncoated f = 75 cm lens (vendor-specified for 588 nm) to produce images on a $1/3''$ CCD sensor of Flea2 camera model FL2-08S2M [25].

The focal length of a lens depends on the wavelength. For the lens in this newly developed beam profile measurement system, its focal length is first determined using an available 534.5 nm laser and a single lens system composed of a crosshair target, the lens and a CCD camera. The measured focal length is 75.1 ± 0.3 cm, which agrees well with the number from the lensmaker's data, 74.9 cm at this wavelength. The focal length at 340 nm is calculated using the index of refraction of the lens material at 340 nm and 534.5 nm, with a result of $f\,(\lambda = 340\text{ nm}) = 72.2 \pm 0.3$ cm.

2.2. Characterization of the CCD camera

For the CCD camera, three important sets of properties have been studied: (1) the pixel size of the CCD sensor, (2) the exposure time and (3) the gain. The pixel size is measured using a single lens imaging system similar to the focal length measurement system described above. The only difference is that the crosshair target is replaced by a steel ruler with equally spaced markings. The measured CCD pixel size is 4.65 ± 0.01 μm in the horizontal direction and 4.67 ± 0.02 μm in the vertical direction, which agrees well with the vendor's specification, $4.65\ \mu\text{m} \times 4.65\ \mu\text{m}$.

To obtain accurate beam size results, the exposure time is adjusted so that the maximum intensity of the image is kept around 80%–90% of the maximum intensity (i.e. pixel values between 200 and 225 for this 8-bit CCD). The relationship between the total intensity of the image and the exposure time is studied using synchrotron radiation at different electron beam currents. The results show that the total intensity of the image normalized by the electron beam current has a linear dependency with the exposure time from 1 to 66 ms.

The beam profile measurement system is developed to have a very large dynamic range. In particular, it needs to work well in very low beam current situations (i.e. a few μA). The combination of the exposure time and CCD gain is used to handle low intensity beam images. After maximizing the exposure time (66 ms), the CCD gain can be increased to boost the image intensity.

Based on the characterization results of the lens and the CCD camera, a few important parameters of the newly developed beam profile measurement system are collected in Table 1.

3. Reduction of the diffraction effect

In the beam profile measurement system, the electron beam image is projected onto the CCD sensor by the synchrotron light. The electron distribution can be considered to be an input signal, and the image intensity distribution is considered to be an output signal. Therewith, the image of the synchrotron radiation from an electron beam of the zero size can be considered as an impulse response (a diffraction pattern).