PHASE SPACE MEASUREMENT USING AN X-RAY PINHOLE CAMERA AT SSRF

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Abstract

Since 2009 an X-ray pinhole camera that has been used to present the transverse beam size on diagnostic beamline of the storage ring in Shanghai Synchrotron Radiation Facility (SSRF). Transverse beam profiles in the real(x,y) and phase (Y,Y') spaces are obtained by an X--ray pinhole camera sensitive by moving one pinhole. The large amount of collected data has allowed a detailed reconstruction of the transverse phase space evolution in this paper. An image on a fluorescent screen is observed by a CCD camera，digitized and stored, then the phase space and the real space profiles are reconstructed. A non — linear least square program fits the resultant profiles to a vertical dimensional Gaussian distributions to derive the phase space and emittances for SSRF storage ring.

INTRODUCTION

Measurement bunch size, the diffraction effect is very obvious, simple imaging systematic measurement error is large, the use of X-ray imaging system to measure the bunch size, can increase the resolution.[1][2] When using an x-ray pinhole camera to measure phase space, a pinhole cannot see the whole beam vertically, because of the small opening angle of the radiation. The following two methods were tried to solve this problem. The first measurement was made by moving the pinhole vertically. The second was made by using multiple pinhole plate. An image on a fluorescent screen is observed by a digitize CCD camera, and stored. The phase space and the real space profiles are then reconstructed. A nonlinear least square program fits the resultant profiles to a two dimensional Gaussian distributions to get the Twiss parameters and emittances. The first one has been used at SSRF.

PINHOLE CAMERA SETUP

An X-ray pinhole camera has been installed and operating since 2009 at the storage ring of SSRF. In Shanghai synchrotron radiation facility (SSRF) storage ring, the pinhole and imaging system are in air, and the X-ray beam from the bending magnet, X-ray pinhole camera system consists of the front end, attenuators, holes, YAG target, camera and PXI Controller and image acquisition, etc., and data acquisition and processing software platform developed using Labview, and control system interface through EPICS Shared. Memory IOC core technology.

X-Ray Diagnostic Beamline Layout

The layout of the X-ray pinhole camera system is shown in Fig. 1.

The synchrotron radiation exports from a copper block, a rake angle of a few degrees was imposed on the surface to minimize undesired reflections. The defining vertical aperture blades are fixed to a copper plate (10 mm thick) which absorbs most of the radiation except that going through a 2mm diameter hole tapered.

The pinhole is actually an array of pinholes that transverse dimension can be flexibly switched. An array of 3 x 3 rectangular pinholes was made from 3 pairs of tungsten plates which is 3.0 mm thick, 10mm wide, and 25mm long. The distance between every plates of tungsten are respectively 20μm，50μm，100 μm, each with a set of horizontal and vertical. The large pinhole is used for alignment purposes using a laser. The small pinholes are used during the measurement. The size 20μm by *50μm pinhole can get good resolution image for high storage current more than 200mA.

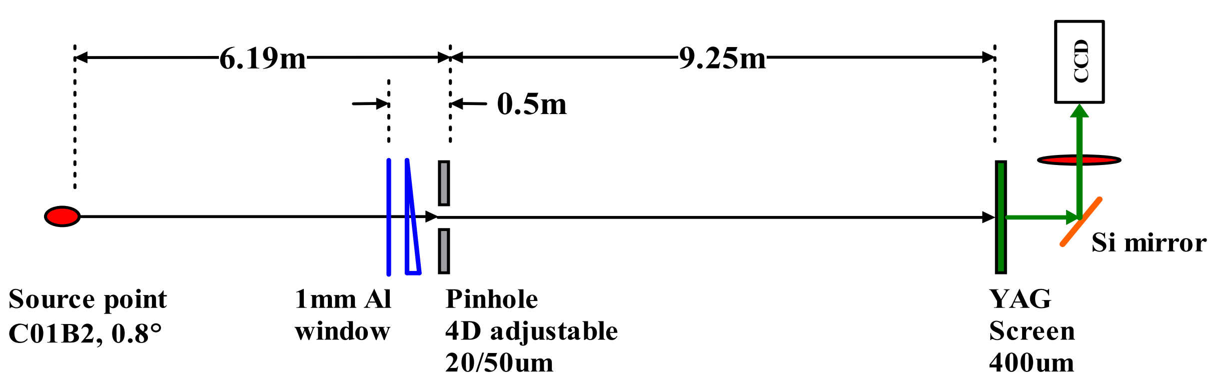

Figure 1: Schematic layout of the X-Ray Diagnostic Beamline viewed from side on.

ISBN 978-3-95450-127-4

Pinhole Camera

The pinhole is placed behind the window, as close as possible from the source, the distance is 6.19 m from the source. (2D gaussian, r.m.s 20 μ m by 50 μ m). A YAG: Ce fluorescent screen was used to get image of source, it absorbs X-rays and fluoresces in the visible. Whole tungsten block of rectangular pinhole can be moving by step motor in four dimensions. A copper wedge-shaped attenuator is place between source and pinhole as shown in Fig. 2.

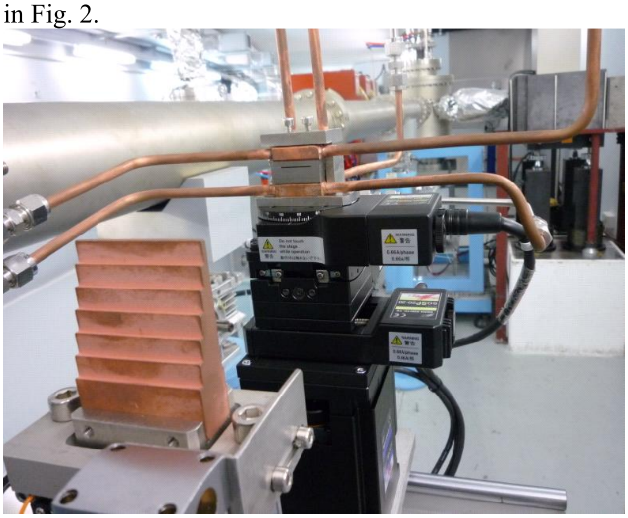

Figure 2: Pinholes with copper wedge-shaped attenuator.

The YAG:Ce phosphor screen is located at 9.25 m away from the pinhole, so that the image is magnified by a factor ≈ 1.49. Only a very small space could be devoted to this detector on BL2. The whole detector includes a YAG:Ce phosphor screen, a Si mirror, a magnifying lens and a CCD camera, it's confined in a 25mm x 215 mm x 250 mm tank.

A wedge-shaped copper block, it can be inserted into the beam by remote control to filter the photon beam. The integration time of the CCD camera is between 0.1 and 30ms and by moving the copper attenuator in and out. Adding filters reduces the intensity of the x-ray beam at high electron beam currents and improves the resolution of the measurements.

PHASE SPACE MEASUREMENT

Emittance is an important property of beam. The invariability of the emittance due to Liouville's theorem makes it a good estimate of the performance of the particle accelerator. It is not directly possible to make a measurement in the phase space but indirect measurements can be made, a measure for the consistency in position momentum phase space.

Video Data Calibration

X-ray pinhole camera has been used phase space measurement at the storage ring of SSRF. The opening angle of the synchrotron radiation in the X—ray region is so small that a pinhole cannot vertically accept the radiation from all particles vertically distributed. So a moving pinhole was chosen both the beam size and divergence can be measure simultaneously. The images have been recorded with the shift distance of pinhole and camera. Both the beam displacement and inclination can be determined from the shift of beam images with respect to the initial position and the shift of images envelope.

The pinhole camera has been calibration by the point spread function (PSF) of the system. PSF include geometrical and diffraction components, also including the screen, the mirror, the lens and the CCD camera is hard to be calculated, but it can be acquired by calibration experiment without any approximation problem. A tungsten blocker was used to assist measure. The differential results of the reference image and the calibration image can be used to get the PSF directly, as described in [3].

For every image, the corresponding Full Width Half Maximum (FWHM) of the point spread function at the source is:

$$W = a\left(1+\frac{d}{D}\right)$$

Here a is the hole diameter. The effect of diffraction can be neglected, in $a >> 2\sqrt{\lambda D}$ case. With the further decrease the size of hole, the resolution of diagnostics is determined mainly by diffraction, and the apparatus function can be written down as; [2]

$$W = \frac{1.1\times10^{-6}d}{E_{ph}(eV)a}$$

Critical energy（Ec）for SSRF: 9.94 keV；Eph is a few Kev, which is the photon energy, eV. It gives a limit to the measured size. The typical resolution of pinhole cameras is approximately a few μm.

In a bending magnet, the curvature of the electron trajectory in the horizontal plane, under the action of the vertical magnetic field, results in an effective horizontal divergence at the source. Large divergence is not the case in the vertical plane; therefore, consider a photon beam with no divergence at all, after passing through an infinitely small pinhole the beam, neglecting diffraction, zero vertical divergence. The experiment has done moving pinhole in vertical.

Phase Space Reconstruction

A Gaussian approximation to the photon distribution from a single electron is an upright ellipse in (y, y‘)) with an angular extent given by $\sigma_{y'}$ and a spatial extent given by σ_y. [5]

$$\sigma_{y'}(mrad) = \frac{0.289}{E(Gev)}\left(\frac{\lambda}{\lambda_{crit}}\right)^{0.425} \quad \text{and}$$

$$\sigma_y\sigma_{y'} = \frac{\lambda}{4\pi}$$

Where E is the electron energy, λ is the wavelength of the synchrotron radiation, and λcrit is the critical

ISBN 978-3-95450-127-4

wavelength. For the wavelengths of interest, σ_y is very small, and can be negligible. The vertical size of the image at the screen is simply ***D/d*** times the vertical electron beam size, it would give a factor of 1.49 in SSRF x ray case.

As shown in Fig. 3, let the radiation intensity distribution in the phase space at the source be I(ys,y0), and that at the screen be, I_1(ys,y0;y). A point (yp.yp') at the source is transformed to the screen by the relation:

$$\begin{pmatrix} y \\ y' \end{pmatrix} = \begin{pmatrix} 1 & d+D \\ 0 & 1 \end{pmatrix} \begin{pmatrix} y_s \\ y_s' \end{pmatrix}$$

Beam current amplitude normalization, data processed from image plane data.

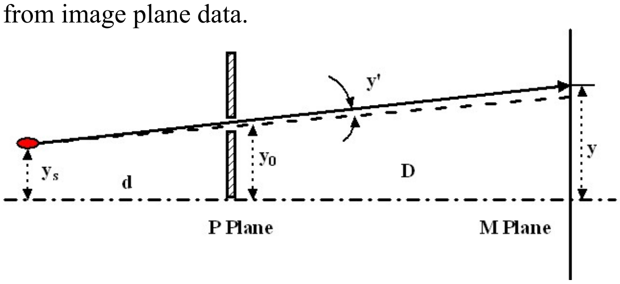

Figure 3: The x-ray incident on a hole to pass through to the screen monitor.

The shift distance of pinhole and camera with beam intensity, depending on the original image data calculated vertical projection profile, the projection data using Gaussian function fitting, each image obtained amplitude (Amp), center position (Pos), width (Sig) three characteristic parameters of the fitting after normalization of the beam current amplitude, data processed image plane data. The translation of these results point to the light source will be done.

For each profile, based on their corresponding holes in the acceptance of a straight line, calculate the light source point in the phase space Y, Y 'coordinate. Depending on the obtained Y, Y ', Profile data contour map can be drawn, namely photon phase space distribution, as shown in Fig. 4.

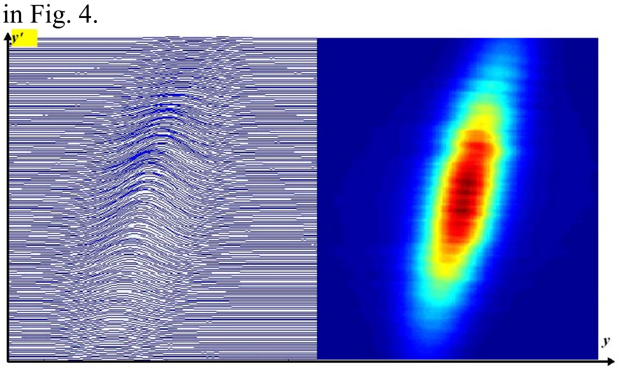

Figure 4: Photon phase space distribution.

The points on the light source corresponding to the pinhole are expressed by a line y'=(y-y_0)/D in the phase space. As given in Fig. 4. The image on the screen I(y,y_0) is the integration of I(y,y';y_0) over y'. i.e. [4].

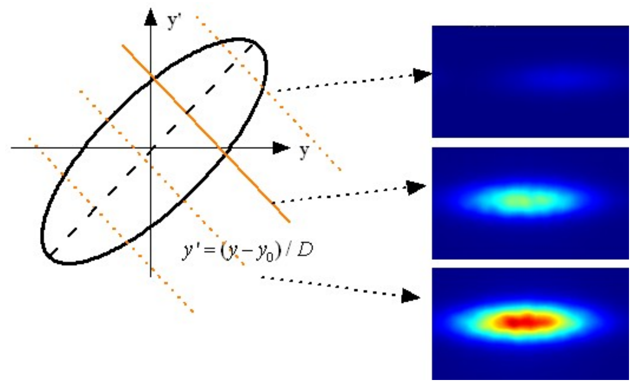

Figure 5: Reconstructing phase space from M plant image information.

A 20 μm identical size hole has been chosen to measure. Ideally the tungsten plate stops the beam, allowing only the x-ray incident on a hole to pass through to the screen monitor. Moving pinhole step by step and adjustment camera to get image corresponding. The total intensity of each beam let as a function of the position of the defining hole still provides a spatial profile of the beam. The profiles of individual beam lets can be used to extract information on the angular distribution of the beam at the position of the hole.

The pinhole plate is shown in Fig. 3 as plane M and the beam monitor as plane P, a distance D from the plane P. The transverse spatial axes x and y are defined on M and a parallel set of axes x_0 and y_0 on P. The origins of these coordinate systems are connected by a line parallel to the optic axis of the beam. A single collimated beam let is shown. If a particle is known to pass through the point (x_0; y_0) on M and strike P at the point (x; y), then the slopes of the particle's path with respect to the optic axis are given by

$$x' = (x - x_0)/D = k(x - x_0)$$

$$y' = (y - y_0)/D = k(y - y_0)$$

$$k = 1/D$$

Thus the beam let spatial profiles in (x; y) are a direct measure of the angular distribution of the beam sampled at (x_0; y_0). So we were moving pinhole in different position and taking the image data of screen to reconstructing phase space from M plant image information as shown in Fig.5. The dashed line is shown the maxima value in the phase space trajectories with a slope k_c as:

$$k_c = \frac{k(Y_c - y_c)}{Y_c} = k - \frac{ky_c}{Y_c}$$

To understand exactly what is imaged by the pinhole camera, one must consider the photon distribution in (x, x', y, y') phase space. The photon distribution is given by the convolution of the electron distribution with the photon distribution from a single electron. The photon distribution from a single electron is not Gaussian, but for x ray using a Gaussian approximation to this distribution will be only negligible very small error to the results.

ISBN 978-3-95450-127-4

CORRECTION EXPERIMENT

In order to get a smaller vertical beam size, methods are chosen that correct betatron coupling and vertical dispersion. If the skew quadrupoles used for coupling correction are included as the fit parameters, the fit result will give the skew quadrupoles strength that produces the same effect. Then the opposite values are used to adjust the vertical emittance to minimize. The experiment of coupling correction was done at SSRF storage ring. The skew quadrupoles strength have used for correction experiment.

When changing the current value of quadrupole magnet Q5, the variation can adjustment coupling. Phase space will be change. It is shown on Fig. 5 while the Q5 current change from 204.7A to 194.7A; the beam size y from 160 μ m to 100 μ m. Emittance is getting smaller. Corresponding tune working points move qx: from 0.2500 to 0.2215 qy: from 0.2846 to 0.2932 at different coupling situations obtained using a scannable pinhole camera, it is shown in Fig. 6.

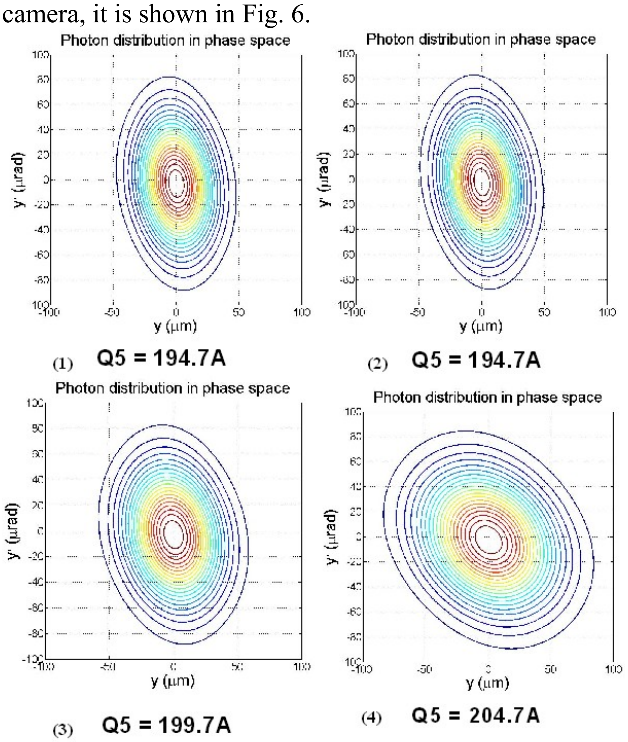

Figure 6: Phase space varied using a skewed quadrupole. Emittance coupling was varied using a skewed quadrupole and is increasing from right to left, down to up((4) to (1)). (Units on the plots are y in μm, y' μrad).

CONCLUSIONS

Commissioning of the SSRF storage ring with nominal energy of 3.5 GeV was started in 2009. The storage ring provides a high brightness source of x-rays from bending magnets. The x-ray pinhole camera has been using to achieve the parameter for beam spot size measurement and real-time monitoring. SSRF storage ring has been designed specifications for the 3.9 nm · rad emittance, how to implement small emittance measurement crucial. Beam emittance and secret nature of the overall transverse oscillation cutting contact with elliptical beam area of the same in different locations, but the shape. Shape is different, so the storage ring beam cross-section shape and envelope undulant Changes with position. This characteristic is determined by the relative position of the oval-shaped Like, that depends on the Twiss parameters. Lattice parameter β measurement by the position monitor, in addition, the need to accurately measure the beam profile. According to Rayleigh Criterion, by the light source wavelength resolution is limited using visible light Measurement bunch size, the diffraction effect is very obvious, simple imaging systematic measurement error is large, the use of X-ray imaging system to measure the bunch size, can increase the resolution.

Coupling correction experiment indicate that more skew quadrupoles are required if a smaller beam emittance is demanded. When the skew quadrupole number rises, the vertical dispersion and the coupling from quadrupole rolls are more corrected.

ACKNOWLEDGMENT

The authors would like to thank the SSRF physical group and beamline mechanical group discuss with us. Technical Services Division in particular the colleagues in the mechanical, vacuum, alignment and control groups. The support provided by the technicians who have contributed to the x-ray pinhole and synchrotron light monitor projects. The useful advice of T. Mituhashi and ESRF colleagues is gratefully acknowledged.

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ISBN 978-3-95450-127-4