EMITTANCE MEASUREMENTS OF A HIGH-CURRENT SINGLE-BUNCH ELECTRON BEAM AT THE PRE-INJECTOR OF THE KEK 2.5-GEV LINAC

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ABSTRACT

Emittance measurements have been performed in order to study the characteristics of a high-current single-bunch electron beam at the pre-injector of the KEK 2.5-GeV linac. It is important to measure the beam emittance so as to obtain the bunching characteristics of electron beams in the KEK B-Factory[1]. An on-line computer system for emittance measurements was constructed. This report describes the hardware and software configurations of the emittance measurement system and some results concerning the experimental measurements for high-current single-bunch electron beams at the pre-injector.

INTRODUCTION

An emittance measurement system using a fluorescent-screen monitor has been developed to diagnose a high-current single-bunch electron beam from the pre-injector of the KEK 2.5-GeV linac newly installed for the KEK B-Factory. This system consists of a fluorescent-screen monitor viewed by a high-resolution asynchronous-reset CCD camera and a commercial video image processor installed on a personal computer (PC). The beam-profile image on the screen monitor is sent out from the CCD camera to a video-processing board as video-image analog signals. The signals are digitized and stored in the video memory of the PC, which analyzes the image data to obtain the spatial beam widths in the horizontal and vertical directions and calculates the beam emittance automatically by changing the strength of an upstream quadrupole magnet.

HARDWARE SYSTEM

The emittance measurement system is shown in Fig. 1. The new pre-injector system of the linac will be presented in detail elsewhere[2]. The fluorescent screen, which is made of 95% Al_2O_3 and CrO_3 (AF995R[3]), was installed at 45° to the beam line in the monitor. The screen monitor is located at a distance of about 60cm after the buncher. An upstream quadrupole (QM0-10) is also located just after the buncher. The length between the screen and the quadrupole is 48cm. The fluorescent light emitted from the center of the screen is received by a commercial CCD camera (TM-720[4]) placed at a distance of about 1m from the screen monitor. This camera can be synchronously controlled with the beam timing. The shutter timing scheme of the camera is shown in Fig. 2. The shutter opens just after 127μs from the trigger signal and closes after an arbitrarily tunable time. The video signals of the camera are sent to a video freezer[4] at the klystron gallery by a 15m-long multicore cable. The video freezer stores the video signals and freezes the video image synchronized with the beam timing. The frozen video signals are sent to the image-processing system (FRM2-512[5]) installed in the PC. The PC displays a beam-profile image on a console display (Fig. 3) and then analyzes it so as to calculate the beam emittance automatically. The PC can also control the quadrupole strength automatically through the linac control system[6].

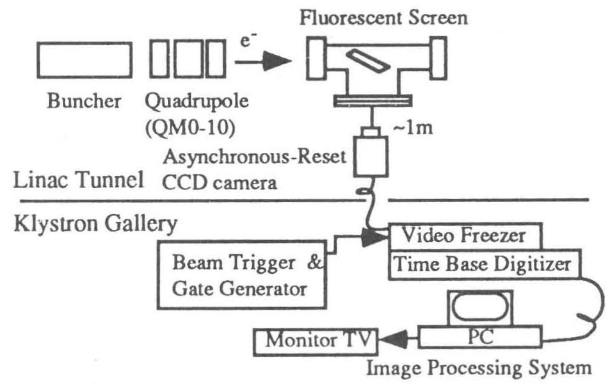

Fig. 1. Emittance measurement system at the pre-injector.

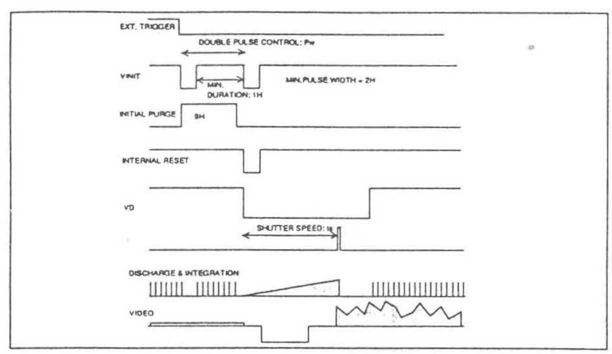

Fig. 2. Block diagram of the shutter control timing of the asynchronous-reset CCD camera.

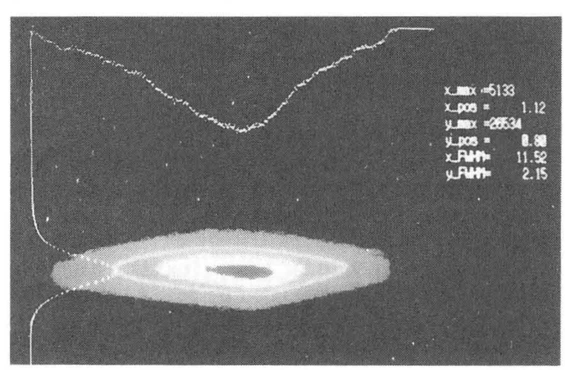

Fig. 3. Beam-profile image on a console display under the condition of a beam current of 7.4nC/pulse. The two curves show the projection

distributions of the beam profile in the horizontal and vertical axes. The intensity of the beam spot is gradated using eight colors.

SOFTWARE SYSTEM

The analog video signal is digitized by the image-processing board. This board has two frame memories (262KB). One frame memory has 512(vertical)×512(horizontal) pixels with a gradation of 8 bits; the effective area, however, is restricted to 486(vertical)×486(horizontal) pixels, because some blanking area is included in the video signal. A lookup table can be set in gradations of 8 bits. The data taking system was mainly written in the computer language C. The spatial resolution of the beam profile on the fluorescent screen is about 16 pixels/mm by using some optical expansion lenses in this system. The spatial resolution is sufficient to measure the width of the beam profile. One of the frame memories is used to store background data under the no-beam condition. The other frame memory is used to store beam-profile data. The data-taking cycle is as follows:

(1) The background data is taken and stored in the frame memory.

(2) The beam-profile data are taken and stored in the second frame memory. The PC reads the data and subtracts the background data from the beam-profile data.

(3) These 512×512 intensity data are integrated along the horizontal and vertical video lines, respectively. These integrated data show the projections of the beam profile in the horizontal and vertical axes. Processes (2) and (3) are repeated several times.

(4) After the above cycle the arithmetic mean and the dispersion of each projection data are calculated and stored on a hard disk of the PC. These projection data are used to derive the beam emittance.

EMITTANCE MEASUREMENT

The beam-profile data were taken at several beam currents (0.79, 3.9, 6.1 and 7.4nC/pulse) by changing the grid-bias voltage of the electron gun. The beam currents were measured by a wall current monitor placed in front of the screen monitor. The emittance measurement (41 data points/1 measurement) was performed by changing the quadrupole currents at steps of 0.1A under a fixed buncher condition. The emittance analysis algorithm can be divided into two main parts. The first is a beam width fitting algorithm by the least-squares fitting procedure of a gaussian curve. The second is emittance fitting by the least-squares fitting procedure using a parabolic function which can be derived from a thin-lens approximation for the transfer matrices of a quadrupole[7].

BEAM WIDTH FITTING

The beam width is calculated by fitting the gaussian curve to the beam-projection data on the horizontal and vertical axes (described in the previous section). The smoothing correction was performed to the beam-projection data in order to reject some data points generated by dead (or noisy) CCD pixels before using the gaussian fitting. The condition of the data rejection criterion is that when the data points are apart from the arithmetic means calculated by the neighboring (or the alternate neighbors) points at the 3σ error level, their data points are rejected. This correction can prevent any misfitting from the gaussian curve. The formula of the gaussian function (G(x)) is defined by

$$G(x) = a_1 \exp[\frac{-(x-a_2)^2}{2a_3^2}] + a_4, \qquad (1)$$

where x is the horizontal (vertical) coordinate of the beam projection, a_1 the peak intensity, a_2 the horizontal (vertical) position at the peak intensity, a_3 the beam width, and a_4 the offset parameter. The 1σ beam widths were used in emittance calculations. The four parameters a_i (i=1-4) are determined by the least-squares fitting procedure[8]. The fitted parameters and their errors are derived from the error matrices (ε_{ij}) as follows [8]:

$$a_j = \Sigma \varepsilon_{jk}\beta_k, \quad \beta_k = \Sigma\left\{\frac{1}{\sigma^2_i}[y_i - G(x_i)]\frac{\partial G(x_i)}{\partial a_k}\right\},$$
$$\varepsilon_{jj} = \sum\left[\sigma_i^2\left(\frac{\partial a_j}{\partial y_i}\right)^2\right], \quad \sigma_{a_j}{}^2 = \varepsilon_{jj}. \qquad (2)$$

Figure 4 shows a typical fitting result under the condition of a beam current of 7.4nC/pulse (a quadrupole current of 0A). Generally, in the linac beams, particularly at the pre-injector, a bottom region of the projection distribution, is not gaussian-like, because of beam tails caused by a difference in the bunching conditions and space-charge effects. Thus, a gaussian fitting including the bottom region does not give well fitting results and needs to be applied after rejecting the beam tail in the fitting procedure. Figure 5 shows the variations of the beam width upon changing the intensity cut value to reject beam tail. The beam width (1σ) and reduced chi-squares have convergent values under a suitable fitting condition. In this way, the best fitting results were obtained at the minimum point of the reduced chi-squares (see Fig. 5).

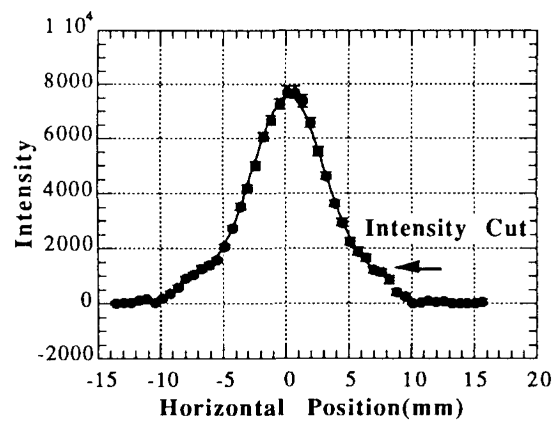

Fig. 4. Typical fitting result of the horizontal beam profile under the condition of a beam current of 7.4nC/pulse (a quadrupole current of 0A). The solid line shows the gaussian-fitted curve. The solid circles show the horizontal data plotted at intervals of ten points.

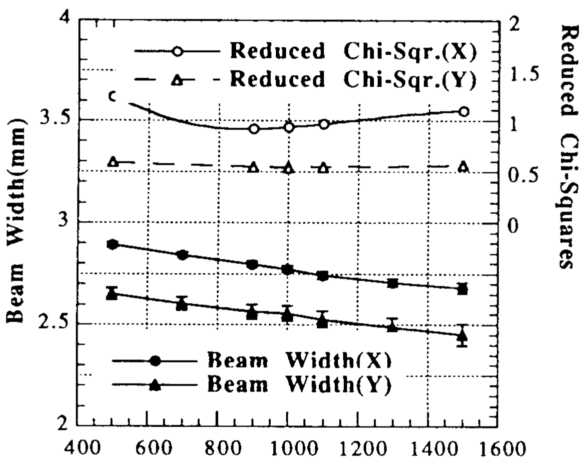

Fig. 5. Fitting characteristics by changing the intensity cut value for the beam tail. The horizontal axis is the cut value of the beam intensity and the vertical axes are the beam width (1σ) and reduced chi-squares.

EMITTANCE ANALYSIS

An emittance analysis was performed by the least-squares fitting using a parabolic function to square of the analyzed beam width. The parabolic function (y) is given by

$$y = a_1(I - a_2)^2 + a_3,$$
$$a_1 = k^2 L^2 \sigma_{11}, \quad a_2 = (1/L + \sigma_{12}/\sigma_{11})/k,$$
$$a_3 = L^2(\sigma_{11} - \sigma_{12}^2/\sigma_{11}), \tag{3}$$
$$k(1/m/A) = 299.79 \cdot g(T/m/A) \cdot L_{eff}(m)/E(MeV).$$

Here a_i (i=1-3) are the fitting parameters, σ_{ij} the components of the σ matrix [7], and L is the length between the screen monitor and the quadrupole magnet; k and g are the focusing strength and the field gradient of the quadrupole, respectively, L_{eff} is the thickness of the quadrupole, and I is the quadrupole current. The beam energy was fixed at 12MeV by a simulation of the pre-injector. The errors of the fitting parameters were derived using the error matrices. The normalized emittance ($\varepsilon^n_{x(y)}$) and the error ($\sigma\varepsilon^n_{x(y)}$) are given by

$$\varepsilon^n = \gamma\beta \cdot \sqrt{a_1 a_3}/k/L^2, \quad \sigma_{\varepsilon^n} = \sqrt{\Sigma\left[\sigma_{a_i}^2\left(\frac{\partial\varepsilon^n}{\partial a_i}\right)^2\right]}. \tag{4}$$

Figure 6 shows a variation of the normalized emittance calculated with the 1σ beam width along the horizontal and vertical axes by changing the beam current. The result did not indicate a clear emittance growth within the errors in the measured range of the beam current.

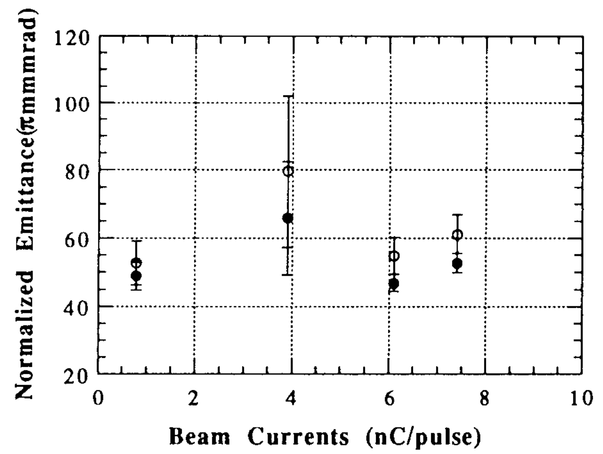

Fig. 6. Variations of the normalized emittance upon changing the beam current. The solid points represent the horizontal emittance and the hollow ones indicate the vertical emittance.

CONCLUSIONS

The automatic emittance measurement system using a fluorescent-screen monitor, has been developed to diagnose a high-current single-bunch electron beam from the pre-injector of the linac newly installed for the KEK B-Factory. The hardware and software system were constructed and tuned for the beam emittance measurement. The beam emittance was measured at several beam currents from 0.79 to 7.4nC/pulse. The normalized emittances in both the horizontal and vertical projections were about 49-61 πmmmrad. The results did not show any clear tendency to emittance growth within the errors. Some reasons can be considered regarding these results. The first is that the best bunching condition might not be applied to higher beam current because of the fixed buncher condition in this experiment. The second is that the beam tail parts of the projection distributions were rejected so as to obtain better gaussian fittings in the beam width-fitting algorithm. A more precise analysis is in progress.

ACKNOWLEDGMENT

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