A PROFILE ANALYSIS METHOD FOR HIGH-INTENSITY DC BEAMS USING A THERMOGRAPHIC CAMERA

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Abstract

A new analysis method for the digital-image processing apparatus has been developed to evaluate profiles of high-intensity DC beams from temperature images of irradiated-thin foils. Numerical calculations were performed to examine the reliability and the performance of the profile analysis method. To simulate the temperature images acquired by a thermographic camera, temperature distributions were numerically calculated for various beam parameters. The noises in the temperature images, which are added by the camera sensor, were also simulated to be taken its effect into account. By using the profile analysis method, the beam profiles were evaluated from the simulated-temperature images, and they were compared with the exact solution of the beam profiles. We found that the profile analysis method is adaptable over a wide beam current range of ∼0.1−20 μA, even if a general-purpose thermographic camera with rather high noise ($\Delta T_{\rm NETD} \simeq$ 0.3 K; NETD: Noise Equivalent Temperature Difference) is employed.

INTRODUCTION

Beam profile measurement in a beam transport line is important for providing high-quality beams at accelerator facilities. To measure the beam profile, one can employ several types of beam monitors, such as wire monitors and scintillation screens [1]. Wire monitors such as wire scanners and profile grids have a high tolerance for high-current beams, and are thus widely used, especially in high-intensity accelerator facilities. However, when measuring beam profiles including hollow structures, the wire monitors fail to give the correct profile, because information from wire monitors is a one-dimensional projection of the beam profile along the x- or y-axes [1]. Scintillation screens are also employed to measure the profiles of high-intensity beams, but are not suited to measure high duty factor DC beams because the CCD camera pixels usually used in scintillation screen systems are easily damaged by secondary neutrons. A new improved monitor is required for the stable measurements of the beam profile in high-intensity accelerator facilities.

Under those background, we proposed a simple diagnostic system including a thermographic camera and a thin foil, in which the heat source distribution caused by beam irradiation and heat conduction can be treated as two-dimensional. The microbolometer used in the thermographic camera is tolerant of neutron radiation in the accelerator facilities that provide high-intensity DC beams[2]. Also, the diagnostic system can be quasi-nondestructive if the target plate can be thin for the incident beams. For those reasons, the simple diagnostic system can be expected to be used in high-intensity accelerator facilities. To evaluate an accurate beam profile from the temperature distribution obtained by the thermographic camera, we developed a new algorithm for a digital image processing apparatuses. The algorithm accurately converts a temperature profile to a beam profile using a discretized Poisson equation with averaging and filtering procedures.

Temperature images acquired by a thermographic camera contain noise from the camera sensors. To investigate degradation of the converted beam profile due to noise and evaluate reliability of the algorithm, we performed numerical analyses using simulated temperature images. To simulate temperature images acquired by a thermographic camera, temperature distributions were numerically calculated for various beam parameters. Camera noise was also simulated to consider its effect. We then converted the simulated temperature images into beam profiles using the algorithm. The converted beam profiles were compared with exact solutions of the beam profiles. We present the results of the comparison between the converted beam profiles and the exact solutions. From these results, we discuss how noise in the temperature images affects the accuracy of converted beam profiles. We then examine the effect of averaging and filtering procedures to obtain more accurate beam profiles.

CONVERSION ALGORITHM

The simple diagnostic system including a thermographic camera and thin foil is shown in Fig. 1. Beams incident on the thin foil pass through it. The beams then irradiate the main target, which is installed downstream for the primary purpose, such as radioisotope or neutron beam production. A thermographic camera installed at an angle diagonal to the beam axis measures the temperature distribution in the thin foil.

The conversion method requires simplification to minimize its calculation cost for use in digital image processing apparatuses. The conversion method is therefore represented by a two-dimensional rather than three-dimensional model. If the beam intensity is constant, and the foil is thin enough to consider energy deposition of the incident beams as uniform along the z-axis, then the relation between the temperature distribution $T(x, y)$ and the heat-source distribution caused by the incident beams $S(x, y)$ is expressed by a two-dimensional steady-state heat conduction equation,

$$\frac{\partial^2 T(x,y)}{\partial x^2} + \frac{\partial^2 T(x,y)}{\partial y^2} = -S(x,y)/\lambda(T). \qquad (1)$$

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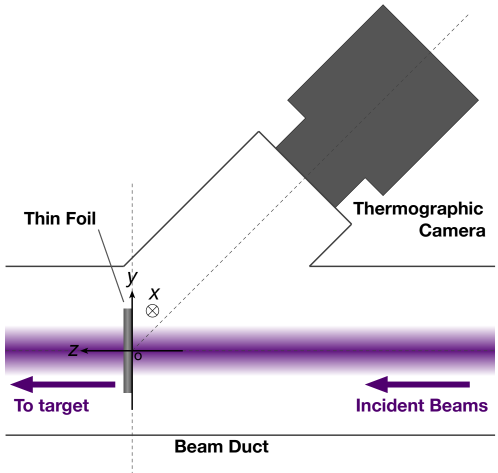

Figure 1: Apparatus for temperature distribution measurement.

Here, $\lambda(x, y)$ is the temperature-dependent thermal conductivity coefficient of the thin foil material. By discretizing this equation using a second-order difference method, we have

$$S_{i,j} = -\lambda_{i,j}\left(\frac{T_{i+1,j} - 2T_{i,j} + T_{i-1,j}}{\Delta x^2} + \frac{T_{i,j+1} - 2T_{i,j} + T_{i,j-1}}{\Delta y^2}\right). \quad (2)$$

Here, Δx and Δy are the x- and y-direction length represented by each pixel, and the subscripts i and j denote the pixel position along the x- and y-axes, respectively. $S_{i,j}$ and $T_{i,j}$ are the heat source and temperature on the (i, j) pixel, respectively. This equation shows that we can obtain the heat source $S_{i,j}$ from the temperature on the pixel (i, j) and the temperatures of its four neighbor pixels by simple multiply–accumulate operations. The beam profile can be evaluated from the heat source distribution by the relation

$$I_{i,j} = qS_{i,j}l_z/\Delta E, \quad (3)$$

where q is the charge state of the incident beams, l_z is the foil thickness, and ΔE is the deposition energy of the incident beams. Note that using this conversion method gives the absolute value of the beam current density distribution as the beam profile only by measuring the temperature distribution.

The conversion algorithm includes averaging and filtering procedures as well as the conversion method of Eq. (2) and Eq. (3), to successfully convert the noise containing temperature images. The flowchart of the conversion algorithm is shown in Fig. 2.

NUMERICAL ANALYSIS METHODS

Temperature distribution images including noise are required to evaluate performance of the conversion algorithm. We therefore simulated the temperature distribution

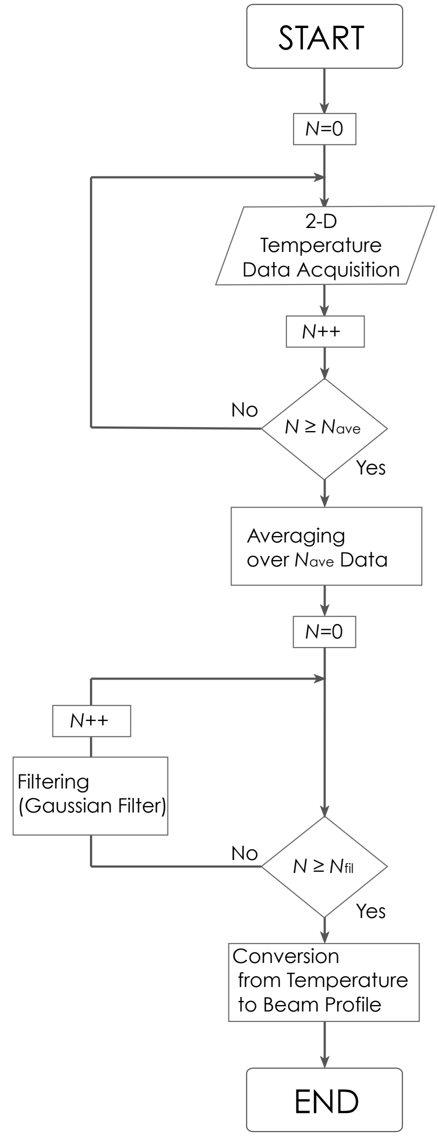

Figure 2: Flowchart of the algorithm.

images by solving Eq. (1) for given beam profiles, assuming that the incident beam currents are constant. Figure 3 shows a schematic diagram of the thin foil system used for numerical analysis. A ϕ100 mm circular region is discretized by 200 × 200 pixels ($\Delta x = \Delta y$ = 0.5 mm). We employed the finite difference method to solve Eq. (1). The energy deposition ΔE of a projectile are calculated using the Bethe-Bloch formula to evaluate $S(x, y)$ in Eq. (1). Pixel noise was simulated using pseudorandom numbers, assuming that the noise amplitude has a Gaussian distribution. The standard deviation of the Gaussian distribution was determined to be $2\sigma = \Delta T_{\mathrm{NETD}}$. The ΔT_{NETD} was assumed to be $\Delta T_{\mathrm{NETD}} = 300$ mK, which is a rather high NETD for general-purpose thermographic cameras [3]. The simulated temperature images of the irradiated thin foil were converted to beam profiles. Then, the converted beam profiles were used for the comparison to the exact solutions of the beam profiles.

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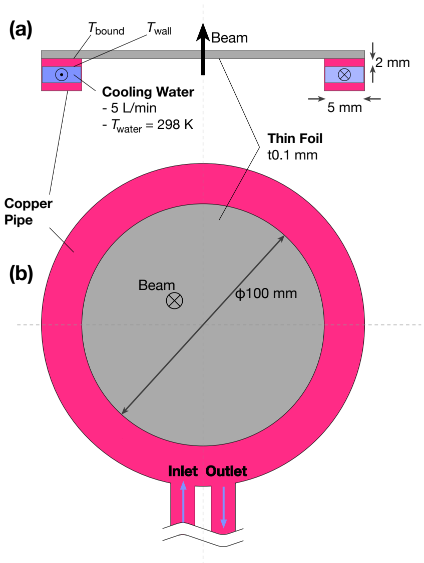

Figure 3: Schematic diagram of the thin foil and the cooling pipe: (a) a cross section, and (b) a bottom view.

solution, as shown in the graph below. We see that the noise amplitude is comparable with the current density of the beam profile (~0.1 μA/mm^2). Since the noise amplitude is too large to measure the beam profile accurately, averaging and filtering are required. Figure 4(b) and (c) show the conversion results using the averaging and filtering procedures. Although the noise on each pixel was still conspicuous when only the averaging procedure was employed (Fig. 4(b)), a single filtering procedure effectively eliminated the noise (Fig. 4(c)). We therefore confirmed that the developed algorithm, including the averaging and filtering procedures, successfully converted the temperature image to a beam profile [4].

CONCLUSION

A new algorithm for digital-image processing apparatuses has been developed to evaluate profiles of high-intensity DC beams from temperature images of irradiated thin foils. The algorithm, which includes a conversion method and averaging and filtering procedures, successfully evaluated profiles of the 20-μA beams from noise-added temperature images ($\Delta T_{\mathrm{NETD}} \simeq 0.3$ K).

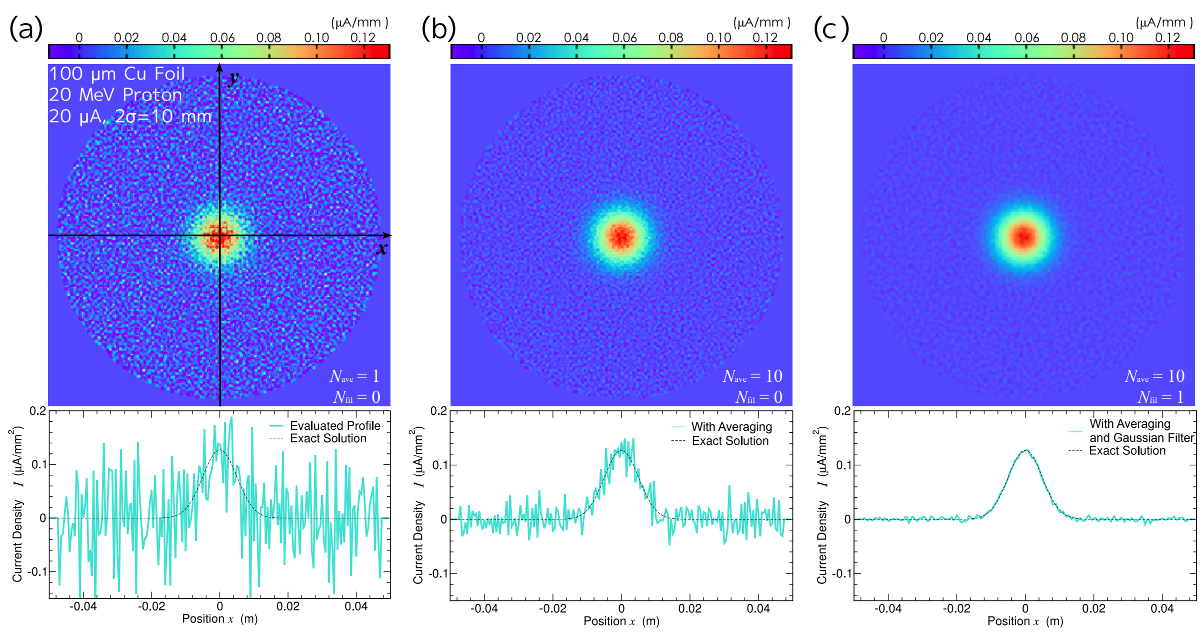

Figure 4: Converted beam profile (a) without any averaging (N_{ave}=0, N_{fil}=0), filtering procedures, (b) using averaging procedures (N_{ave}=10, N_{fil}=0), and (c) using averaging procedures and one-time filtering (N_{ave}=10, N_{fil}=1).

RESULT AND DISCUSSION

Figure 4(a) shows the converted beam profile for a 20 μA, 20 MeV proton beam with a 100 μm Cu thin foil. The converted beam profile was evaluated without any averaging or filtering procedure ($N_{\mathrm{ave}} = 1$, $N_{\mathrm{fil}} = 0$). The beam profile could be observed to a certain extent; however, the noise on each pixel is conspicuous. The converted beam profile along the x-axis is compared with the exact

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