A new method for nondestructively monitoring the position of a charged particle beam in real time

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(Received 10 November 1998; accepted for publication 19 January 1999)

The design and construction of a simple new device for nondestructively monitoring the position of an electron beam is described. By modulating a small portion of the electron-beam current, changes in the amounts of charge induced on the monitor electrodes are detected as currents. These currents are related to the location of the ''center of charge'' of the electron beam. Calculations and experimental results which illustrate the performance of the device are reported. This device is primarily intended for use in electron-beam ion sources and traps, although it could be applied to other situations where the beam current can be modulated.
[S0034-6748(99)00605-X]

I. INTRODUCTION

Of all the techniques used to investigate the properties of matter, the impact of various charged particle beams ranks second only to the incidence of electromagnetic radiation in popularity. Hence, many applications require measurement of the position of a beam of charged particles. Destructive methods (i.e., where the beam is significantly modified during the measurement process) include a modulation technique described by Crapper *et al.*[1] This technique is not feasible for high-current, high-energy beams, due to the power heating produced. For such an electron beam, in the presence of other matter (i.e., neutral background gas or ions), Levine *et al.*[2] determined the profile, and hence, the position of the beam by imaging the x rays it emitted using a pinhole camera. Imaging using a curved crystal[3] could also be used to determine the position of a high-energy beam. These imaging techniques, although providing other useful parameters such as the temperature of an ensemble of confined ions or width of the electron beam, are not practical for real-time determination of the position since they require several hours acquisition time.

The magnetic field produced by a moving charged particle beam can be measured. Using a flux coupling coil with a superconducting quantum interference device,[4] a sensitivity of 1 nA has been achieved. These devices provide fantastic sensitivity but they are expensive and quite bulky, requiring a few liters of free space around the beam. In ring-based experiments, a somewhat less sensitive technique makes explicit use of the time structure associated with the orbital period of the beam.[5] In this case, the Fourier transform of the noise signal is used to relate the inherent time structure to properties of the beam.

Our new monitor is intended for linear beams, such as those commonly found in EBITs and EBIs,[6] although it could be used in other charged particle beam devices where the current has an inherent time structure or such a time structure can be conveniently imposed.[7] It has been installed in the Tokyo EBIT (Ref. 8) to allow us to monitor the beam's position while the device is in use. In our application, the device is used to ensure reproducibility of tuning from run to run for spectroscopy, ion extraction, and so on. In this application, the relative beam position as opposed to the absolute position is of primary importance. However, the device could easily be used to perform absolute position measurements. Due to its simplicity, the monitor is quite robust, and can be operated in the presence of magnetic fields or moderate levels of radiation. The monitor, however, requires an electrostatically field-free region for operation.

II. BEAM MONITOR CONFIGURATION

The layout of our monitor is shown in Fig. 1. It works by exploiting the capacitive coupling between the monitor electrodes and the electron beam. In analysis of the monitor's performance and in its practical use, the difference between the currents flowing out of a pair of electrodes which have faces parallel to each other is a particularly important quantity. Hence, when we refer to a ''pair of electrodes,'' we mean two electrodes which have their faces parallel and we consider the monitor to be two such pairs.

We detect the changes in the induced charges (i.e., currents) on the sensor electrodes, as the electron-beam current is modulated. Symmetry dictates that the currents on opposite electrodes should be equal when the beam is centered. A simple model, which we present later, predicts that near the center of the monitor electrodes, the difference in currents flowing out of a pair of electrodes is approximately proportional to the displacement of the beam from the center position.

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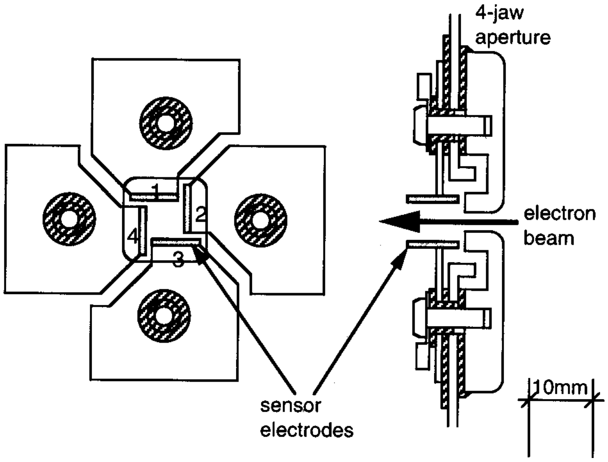

FIG. 1. Scale diagram of the beam monitor. Diagonally striped regions indicate insulators. Dotted regions show the sensor electrodes.

III. ANALYTICAL MODEL

The difference between the induced charges q_1 and q_3 must be an odd function of the position:

$$q_1 - q_3 = k\Delta x + O(\Delta x^3), \tag{1}$$

where q_i is the total charge on the ith electrode and Δx is the displacement of the electron beam from the center, in the direction perpendicular to the faces of the 1,3 pair of electrodes as defined in Fig. 1. The difference $q_1 - q_3$ can be represented by a power series containing only odd powers of Δx due to the symmetry of the system.

For a small displacement from the center, we can treat the displaced beam as the sum of an electrostatic dipole and the centered beam. It can be shown using the method of image charges, that a dipole lying in between a pair of infinite parallel plates with its axis perpendicular to them, induces charges on the plates which gives rise to a dipole of equal magnitude but opposite direction. Using this result and the principle of superposition, we can estimate the constant k:

$$\partial q_1 = -\partial q_3 = \frac{\Delta x}{d} Q, \tag{2}$$

and hence,

$$k = \frac{2Q}{d}, \tag{3}$$

where Q is the charge in the electron beam which is inducing the charges on the sensor electrodes and d the separation of the parallel plates. The assumption that the dipoles cancel is not valid for finite, parallel plates. Hence, it is an approximation in this application.

For measurement purposes, it is convenient to convert the signal to a voltage and amplify it. Connecting the pair of plates with a resistor R and then using an amplifier with a voltage gain G, gives rise to an output voltage:

$$V(t) = \frac{2G\Delta x R}{d} \frac{\partial Q}{\partial t}. \tag{4}$$

Considering the total charge in the length of the electron beam, which the monitor senses, (l) and beam current I, when the particles in the beam have a velocity ν, we get

$$V(t) = \frac{2Gl\Delta x R}{\nu d} \frac{\partial I}{\partial t}. \tag{5}$$

This model predicts that the output signal is proportional to the displacement of the electron beam from the center. The constant of proportionality is related to various geometrical factors and values of electrical components which may readily be determined. In practice, the hardest parameter to determine is l, the length of the charged particle beam which induces charge. This factor is, however, rigorously included in the computational treatment outlined below. In our device, before and after the monitor, the electron beam passes through grounded apertures. These apertures act to limit the length of the electron beam which induces charge in the sensor electrodes. Since these apertures are close to the sensors, we might expect l to be similar to the length of the sensor electrodes.

In practice, the electron beam has a finite size so it is important to define exactly what is meant by the position of the electron beam. Since Coulomb's law is isomorphic with Newton's law of gravitation, we can define a quantity analogous to the center of mass, using charge in place of mass. We call this quantity the ''center of charge'' of the electron beam. Hence, any section of the beam can be treated as a section of an infinitesimal beam with the same center of charge. We see from the above argument that the quantity such a monitor measures is then the position of the center of charge of the section of the beam passing through the monitor.

IV. COMPUTATIONAL MODEL

The model developed in the previous section is suitable for a beam monitor which has a high degree of symmetry and ideal geometry. For a real device with the electrode structure shown in Fig. 1, Eq. (5) must be generalized to

$$V(t) = \frac{GkR}{\nu} \frac{\partial I}{\partial t} [\Delta x + \alpha \Delta y + O(\Delta^3)]. \tag{6}$$

The constants k and α are related to the beam monitor geometry. These constants can be determined by considering the charge-density distribution induced on each electrode. Every metal surface is represented by many small rectangular elements. The charge density across each of these finite elements was considered to be a constant. Since the potential induced by these charge elements must exactly cancel the potential induced by the electron beam (all the electrodes are grounded), these constant charge densities can then be determined by solving an inversion problem. The matrix equation for the charge densities on the electrodes (represented by the vector $\boldsymbol{\sigma}$) is

$$\mathbf{A} \cdot \boldsymbol{\sigma} + \mathbf{V} = \mathbf{0}. \tag{7}$$

A is a matrix which represents the electrostatic coupling among rectangles. Its elements can be calculated in a closed form.[9] The induced charges are given by $\boldsymbol{\sigma} = -\mathbf{A}^{-1} \cdot \mathbf{V}$ for any beam trajectory through the monitor. **V** is a vector representing the potential on an electrode due to the electron beam alone. Elements of **V** can be calculated from Gauss' theorem since the beam is cylindrically symmetric.

The expressions used for calculating the elements of **A** and **V** are of a similar nature. They both represent the potential at the field point due to integration over a source distribution. The resultant expressions were expressed so that the field point was at the origin and the charged plate (elements of **A**) or rod (elements of **V**) had a particular orientation. Before using these expressions to calculate the elements of **A** and **V**, rotational and translational transformations were made.

Care was taken to split the integral over the source terms into two or four integrals when required. This procedure is required when there is a point (or set of points for calculation of **A**) in the source distribution closer to the field point than any of the points bounding the source distribution. Splitting the source distribution into two new distributions where the closest point now lies on the division, gives two integrals (or four in some cases for calculation of **A**), which must be evaluated. The procedure for splitting source distributions in evaluating the integrals can be treated algorithmically as a series of decisions. Since all the integrals are finally evaluated analytically, the calculation of **A** and **V** can be done with modest computer power.

V is linear in η, the charge per unit length in the electron beam. Hence, the change in induced charges for different beam currents or velocities can easily be calculated from a single calculation of σ, for a particular value of η by linear scaling. The elements of **A** and **V**, however, need to be calculated for various positions of the electron beam to determine the variation of induced charges (and, hence, the signal from the monitor).

The total charge induced on a particular electrode is simply the sum $\Sigma_i \sigma_i S_i$ where the summation includes all finite elements which comprise the electrode and no others, σ_i are charge densities taken from the vector σ and S_i are the areas of the finite elements.

We calculated the charge induced on each electrode, varying the position of the electron beam. Calculations were made corresponding to a grid of electron-beam positions. By fitting the functional dependence of the difference in the total induced charge on a pair of opposite electrodes, we were able to determine the constants $k = 4.4$ C/m and $\alpha = 0.2$ for our monitor geometry. We were also able to confirm that higher-order terms were negligible, provided the electron beam was in a square region, with both displacements from the center being bounded by $\pm d/10$. In some applications, the beam may not be perpendicular to the monitor. Our calculations showed that for a straight beam, its tilt with respect to the monitor is not important provided the beam enters the front and leaves the back of the monitor within this same square bounded by $\pm d/10$. In this case, the monitor gives a signal proportional to the average position through the monitor.

We checked the calculations' convergence by increasing the number of rectangles. It is worth noting that the value $k = 4.4$ C/m is somewhat larger than we would expect from Eq. (5) (i.e., the analytical model), which gives $k = 3.3$ C/m when l is set equal to the length of the sensor electrodes. We attribute this difference to be mainly due to the analytical model's failure to account for field penetration through the apertures of the shield electrodes and the effect of charges induced on the inside faces of the shield electrodes. In a simple picture, the shield electrodes can be seen as partial mirrors for induced charges on the sensor electrodes. The effect of these partial mirrors is to increase the effective length of the sensor electrodes, and hence, increase the value of k.

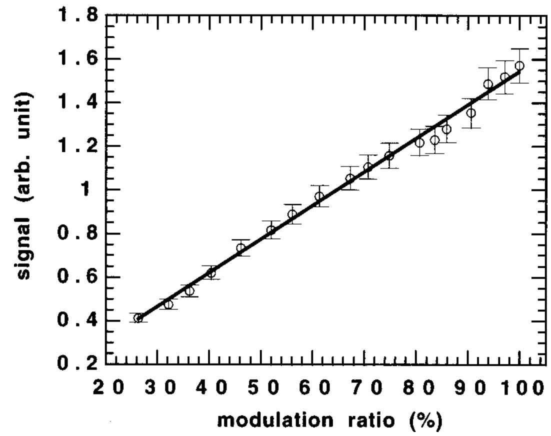

FIG. 2. Measurements showing the linear dependence of the detected signal as a function of current modulation ratio. The unmodulated current was about 80 μA. These measurements were made using a prototype monitor and a television electron gun.

In summary, both the simple model and the computational model predict that for this beam monitor, the output signal is proportional to the percentage modulation of the electron beam [see Eq. (5)], provided that the electron beam is near the center of the monitor. Alternatively, the same equation can be used to say that the output signal is proportional to the electron-beam current for a fixed modulation percentage. Furthermore, the output signal is proportional to the position of the displacement of the center of charge from the center of the beam monitor.

V. EXPERIMENTAL RESULTS AND DISCUSSION

Figures 2 and 3 show the linear dependence of the signal on the current modulation ratio and beam current. These measurements were taken using a prototype device prior to construction of the monitors for use in the EBIT. In this prototype device, the electron beam was produced by an electron gun of the type found in commercial television sets. The beam's energy was 3 keV and its diameter about 1 mm. No magnetic field was used during these measurements.

An example of the time dependence of the output signal is shown in Fig. 4. This measurement was made using one of the monitors installed in the Tokyo EBIT. During this measurement, the monitor was in an axial 4.5 T magnetic field. The current of the EBITs electron beam was modulated by applying a small square wave on top of a large dc voltage to the anode.

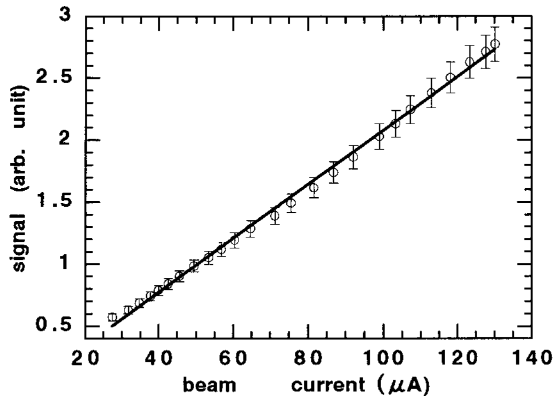

FIG. 3. Measurements showing the linear dependence of the detected signal as a function of electron-beam current with 100% modulation. These measurements were made using a prototype monitor and a television electron gun.

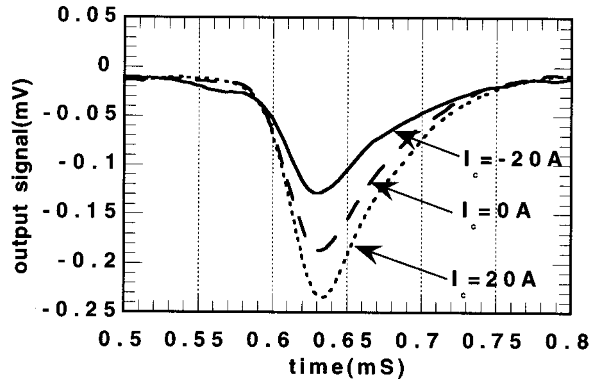

FIG. 5. Change of peak height as the electron beam is steered using magnetic coils. These measurements were made with a beam energy of 28 keV and a current of 125 mA with 10% square-wave modulation at a frequency of 500 Hz. Contributions from both the positive- and negative-going peaks were added together for each data set to improve the statistical quality of the data.

We can clearly see that the resultant wave form has the form expected for the differential of a bandwidth-limited square wave. The bandwidth limitation arises from the slew rates of the power supply used to modulate the anode and the amplifier used to amplify the differential signal from the monitor prior to detection. The measurement took 0.5 s, i.e., 250 oscilloscope shots were averaged to produce the figure shown. The displacement of the electron beam from the monitor's center is proportional to the area under the peak in this trace. Compared to the peak height, this is a better measure to use for deriving the position since it is less sensitive to changes in the bandwidth of the system.

We changed the beam position with magnetic steering coils to see the relationship between the monitor output and currents through the steering coils. The magnetic-field directions do not correspond to the monitor axes, because the locations of the steering coils were determined in part by the structure of the vacuum vessel and the locations of various other pieces of equipment routinely used with the EBIT. The changes in the output signal as the steering coil currents were changed are shown in Fig. 5. As the current through one of the steering coils was changed, we could see the peak area change.

The relationship between the steering coil current and area described is shown in Fig. 6. We derived the absolute position scale from the calculated constants in the model described above. Since the magnetic-field directions do not correspond to the monitor directions, both sets of monitors are sensitive to each steering coil current. By analysis of the deviations from straight lines for the various data shown in Fig. 6, we can easily estimate the reproducibility of the position of the electron beam to within 3 μm with a modulated current of 12 mA and an energy of 28 keV. The absolute determination of the electron-beam position is determined by the accuracy of the construction of the monitor. Our device was constructed to a specified tolerance of better than 20 μm. This tolerance was confirmed by checking the alignment of the monitor to other parts of the EBIT with a traveling microscope.

It is important to confirm that the detected signal is not due to part of the electron beam or secondary electrons it produces, which then hit the sensor electrodes. Capacitive coupling between the electron beam and the sensor plates gives rise to a wave form which is the time derivative of the modulating wave form. Direct impact produces a signal

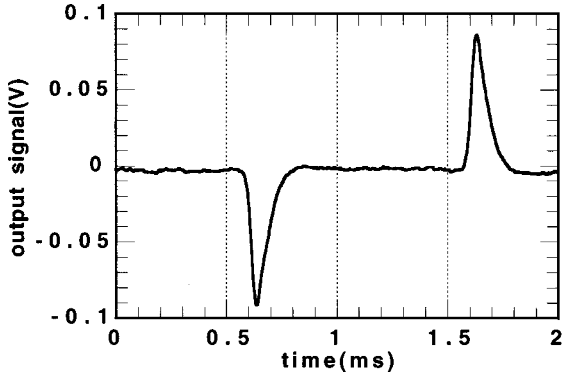

FIG. 4. Time dependence of the observed signal for a beam energy of 28 keV and a current of 125 mA with 10% square-wave modulation at a frequency of 500 Hz.

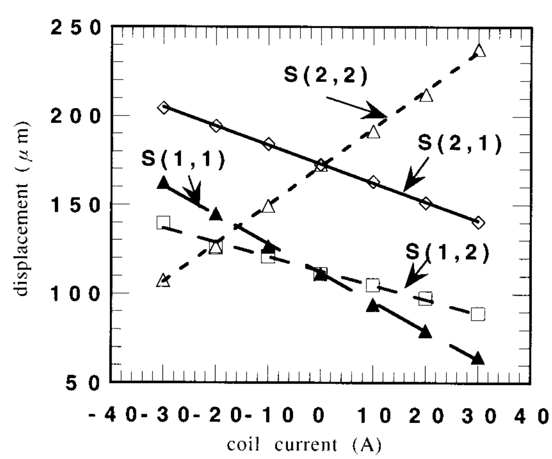

FIG. 6. Electron-beam position measured using the monitor as a function of magnetic field. Four signals are presented with the labeling scheme $S(i,j)$. The index i refers to which pair of electrodes was used to measure the beam position and the index j refers to which pair of coils were used to deflect the beam.

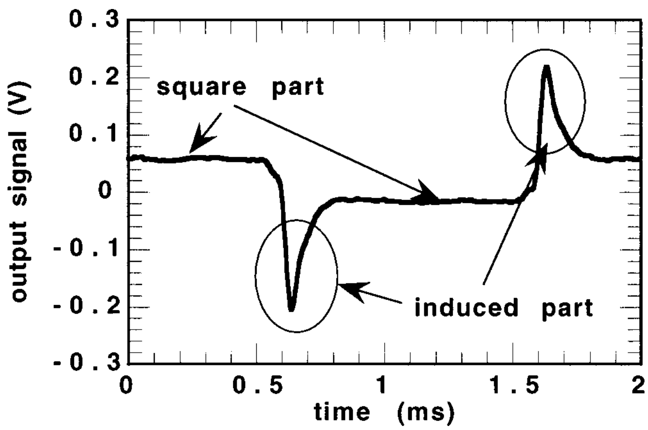

FIG. 7. The measured signal observed when a significant proportion of the electron beam hits one of the sensor electrodes.

which is proportional to the modulating wave form. A composite of these two types of wave forms is observed when part of the beam directly deposits current onto the sensor electrodes as shown in Fig. 7. Here, the steering coils were deliberately mistuned so that a small portion of secondary electrons were able to hit the sensor electrodes. When the electron beam passes clearly through the monitor, the two flat portions occur at the same level as seen in Fig. 4.

VI. DISCUSSION

We have developed a new type of electron-beam monitor and tested its properties. The device proved robust and simple to operate. With this device, we can readily determine the reproducibility in the position of the electron beam within the Tokyo EBIT.

ACKNOWLEDGMENTS

The authors thank Emma Sokell and Ann Currell for fruitful discussions and help in preparing this manuscript.

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