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# Design of a Thin Foil-Type Electron Beam Monitor for 6 Mev Linear Accelerator

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# 6 MeV リニアック用薄膜型電子線モニターの設計

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医用6MeVリニアックによる電子線照射の際に，同時線量測定と電子線偏向制禦を行うために電子線モニターを設計した．このモニターは電子線をさえぎつて挿入され電子線の一部を吸収する金属箔と，高感度の検流計から成つている．検流計の目盛の読みは，フリッケ線量測定値に対して較正し，絶対吸収線量値と対応せしめた．電子線の偏向制禦は，電子線モニターの金属箔部を分割しこの各々に流れる電流のバランスを測定することによつて行つた．さらにこのモニターを電流積算器に接続することによつて，あらかじめセットした値の線量を照射したのち自動的にスイッチを作動させ，電子線をきることが可能になつた．

## Summary

An electron beam monitor for a 6 Mev medical linear accelerator was designed for the simultaneous dosimetry at irradiation and the beam centering. The monitor consisted of a metal foil which was inserted across the path of the electron beam to absorb a fraction of electrons and of a highly sensitive galvanometer. The galvanometer reading was calibrated against the Fricke dosimeter to obtain the absolute absorbed dose. Centering of the beam was controlled by the blance between electric currents given to divided foils of the beam monitor. Automatic switch-off control for electron irradiation with a pre-set dose was made possible by combination of the monitor with the current integrator.

## Introduction

An electron beam produced by a linear accelerator has been applied for radiation therapy of superficial tumors on its benefit of the superficially localized dose distribution. Its significance has been discussed in the symposium on high energy electrons[1]. On the other hand, the electrons from the accelerator are useful for the experiment in radiation biology such as irradiation of the transforming DNA which requires a high dose (order of Mrad) to be inactivated. For both purposes, a reliable and convenient dosimetry for routine use is strongly desired. The problem to be solved is to carry out the dosimetry simul-

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taneously at the time of irradiation without disturbing the electron beam. In addition, it is desirable to acertain that the center of the beam is on the center of the irradiated field. Furthermore, it will be most convenient if the beam can be automatically cut off when a desired dose is delivered.

To fulfill the above requirements, we designed an electron beam monitor in which a part of electron current was absorbed in a thin metal foil which was inserted across the beam and the absorbed current was measured by a highly sensitive galvanometer. The galvanometer reading was calibrated in comparison with the dose measured by the Fricke solution which is believed to be the most reliable dosimeter for high dose-rate radiations. Thus the dose delivered to the patient or to the sample was obtained from the galvanometer reading simultaneously with irradiation. A further improvement made it possible by use of the current integrator and the trigger circuit to irradiate with a pre-set dose and to switch off the beam automatically.

## Materials and Methods

### Linear accelerator

The type of the linear accelerator employed in the present investigation was Varian Model V-7705. The accelerator produced a pulsed beam of 6 Mev electrons with adjustable pulse rate up to 600 pulse/sec. The electrons were accelerated at the horizontal direction along the arm of the accelerator and successively deflected at the vertical direction by two bending magnets. The angle of deflection was controlled by main and fine bending currents. The beam then hit a gold target when X-rays were to be produced. For electron bombardment, the deflected beam was directly introduced to the object to be irradiated. The maximum dose rate at the sample-irradiating position (see Table 1) was approximately 1 Mrad/min without the monitor foil. The maximum electron-beam current as measured from current absorbed in an aluminum block was 4 $\mu$A. For the electron therapy, the accelerator was operated usually at 10 pulse/sec, deliverling 200—1000 rad/min to the skin depending upon the patient position. The accelerator head contained an ionization chamber outside the beam path so that scattered radiations were picked up by the chamber to provide a relative dose. The chamber was connected with the current integrator and successively with the shut-off switch, so that when irradiation with the pre-set recorder counts was completed the shut-off switch was automatically triggered. This trigger unit was available for connection with the

Table 1. Total current reading of the beam monitor with 0.06 mm Cu foil corresponding to the absorbed dose rate as measured by Simplex Universal Dosimeter and by the Fricke solution under different conditions of electron irradiation.

| | Monitor reading | Pulse rate | Distance from edge of shutter | Width of shutter gap | Dose rate rad/min | |
|---|---|---|---|---|---|---|
| | $\mu$V | pulse/sec | cm | cm × cm | Simplex | Fricke |
| Patient treatment range | 1.8 | 7.7 | 60 | 25×30 | 830 | 940 |
| | 〃 | 〃 | 96 | 〃 | 480 | 538 |
| | 〃 | 〃 | 〃 | 10×10 | 234 | 390 |
| | 5 | 14.8 | 〃 | 〃 | 840 | 920 |
| | 20 | 38.3 | 〃 | 〃 | 3,300 | 3,680 |
| DNA irradiation range | 320 | 500 | 10 | 20×20 | * | 660,000 |

* Dosimetry with Simplex dosimeter was impossible because of high dose rate.

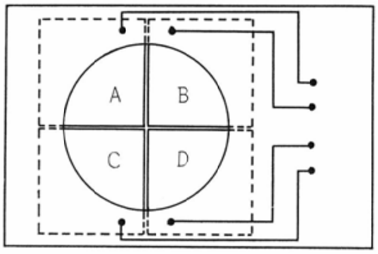
electron absorbing unit as described later. Further technical details about the accelerator have been described by the designers[2].

**Electron-absorbing unit**

The electron-absorbing unit was made of a 0.06 mm thick copper foil (see Figs 1 and 2) and inserted across the path of the out-put electron beam (see Figs 3 and 4). The range of 6 Mev electrons is 3000 mg/$cm^2$ or 3.4 mm in copper. A small fraction of electrons were absorbed by the foil and the majority penetrated through. The foil was divided in four parts and electrically insulated to each other, so that the electron current given to each quadrant could be measured separately. The foil was cemented on a polyethylene sheet and the sheet was further cemented on an aluminum frame (see Fig. 1b). The minimum detectable limit of the beam intensity with a copper foil was 4 pulse/sec. In an alternative method, a 0.1 mm thick aluminum foil was used, by which the monitor could detect the absorbed current from the beam gene-

Fig. 1a and 1b. Diagrams of the electron-absorbing unit of the beam monitor showing vertical (a) and crossectional views (b).

(a)




(b)

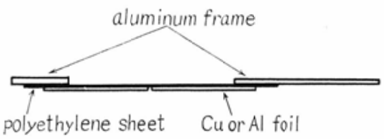



Fig. 2a and 2b. Photographs of the electron-absorbing unit taken from back side (a) and upper side (b).

(a) (b)

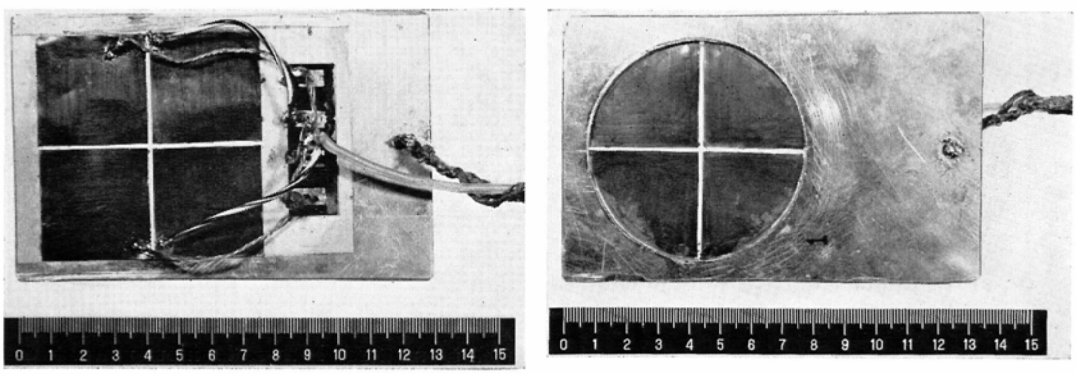


Fig. 3. Photograph of the linear accelerator head showing the insertion of the electron-absorbing unit.

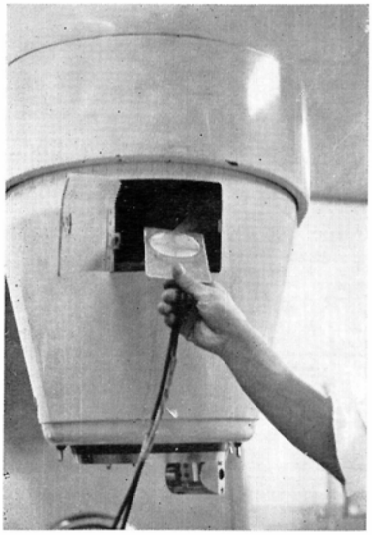
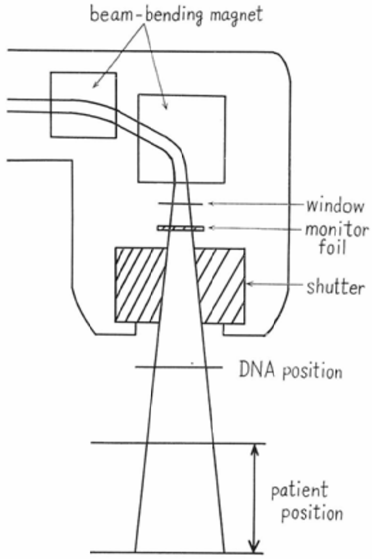


Fig. 4. Diagram showing the crossection of the accelerator head.

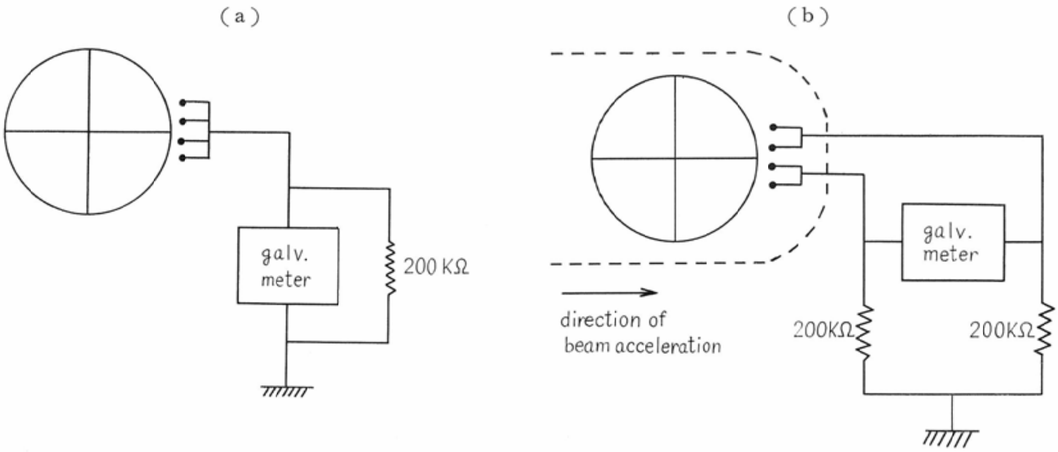



rated at more than 10 pulse/sec. The aluminum foil was sued for the beam-centering experiment.

**Galvanometer**

A highly sensitive galvanometer (Yokokawa Electric Co. Model VN-11, transistor type, measurable range: 0.2 $\mu$V—50 mV) was employed. The out-put of the electron-absorbing unit was connected with the galvanometer as shown in Figure 5a or 5b, depending upon the purpose of measurement.

Fig. 5a and 5b. Diagrams showing electric circuit for measurement of the total absorbed current to the monitor foil (a) and the balance current between divided foils (b).




**Amplifier and integrator for automatic switch-off**

In order to operate the electric current integrator which was originally designed as part of the linear accelerator for connection with ionization chamber to pick up scattered X-rays, the input power to the integrator was required to be more than 100 mV. The electric current from the electron-absorbing unit was amplified by the galvanometer up to 5 mV, so that more than 20 times amplification was further needed. To fulfill the requiremtnt, a direct current amplifier (Yokokawa Electric Co. Model EM-All, transistor-chopper type, maximum amplification: ×100) was employed. The output of the amplifier was connected with the current integrator and subsequently with the automatic shut-off switch as shown schematically in Figure 6.

**Dosimetry**

Dosimetry at irradiation with high dose rate was carried out with the Fricke solution[3]. The measurable dose range of the Fricke dosimeter was from 2 to 30 Krad. At dose rate lower than 5 Krad/min, both of the Fricke solution and Simplex Universal Dosimeter were used.

**Pulse rate control**

The pulse rate of the electron beam was adjusted to a desirable value by comparing the beam pulses with the generator-produced pulses by help of a synchroscope.

## Results and Discussion

**Relationship between the reading of the beam monitor and the absorbed dose rate**

The primary aim of designing the electron beam monitor was to obtain the absorbed dose from the monitor reading. At first, the total electric current absorbed by the foil of the electron-absorbing unit

Fig. 6. Schematic diagram of the combined units by which both of the absorbed current to the monitor foil and the integral current are measured and the beam is automatically shut off when the pre-set dose is delivered.

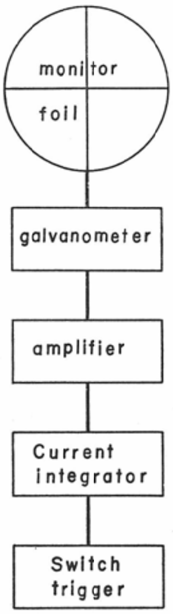
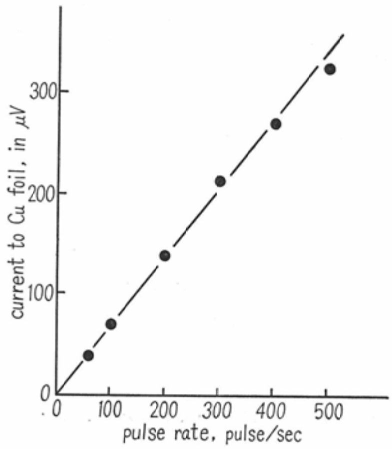



Fig. 7. The reading of the total absorbed current to the monitor foil (0.06 mm Cu) plotted against the pulse rate of the electron beam. The monitor reading shows a linear response to the pulse rate of the beam, i. e., to the beam intensity.



was measured by the galvanometer. Figure 7 shows the galvanometer reading of the total current plotted as a function of the pulse rate of the electron beam, indicating a linear response of the absorbed current to the pulse rate. Thus it is thought that the monitor reading is proportional also to the electron beam intensity or to the absorbed dose rate.

For the measurement of the aboslute dose, the Fricke solution was irradiated in a glass tube (1 cm in diameter) at different positions. Figure 8 shows the optical density of the Fricke solution (Fricke O. D.) plotted against different doses of electrons. The irradiation was performed at the maximum dose rate (approx. 1 Mrad/min) without the monitor foil at the distance 10 cm from the edge of the beam shutter. The relative dose was determined by the monitor ionization chamber. The absolute dose was calculated from the Fricke O.D. multiplied by the extinction coefficient for the $Fe^{++} \rightarrow Fe^{+++}$ oxidation at the given temperature. It is shown in Figure 8 that the Fricke O.D. responds linearly to the electron dose in the dose range employed.

On the other hand, Figure 9 shows the Fricke response to the different dose rate with the monitor foil. The Fricke O.D. per unit integral dose as determined by the monitor ionization chamber was plotted against the increasing electron beam intensity as measured by the pulse rate of the beam or the total current to the monitor foil.It was shown that the Fricke response is independent of the beam intensity or the dose rate in the employed dose rate range up to 0.66 Mrad/min.

Fig. 8. Optical density of the Fricke solution irradiated with different doses of electrons at the maximum dose rate 1 Mrad/min. Relative dose was determined by measuring the scattered radiations with the monitor ionization chamber.

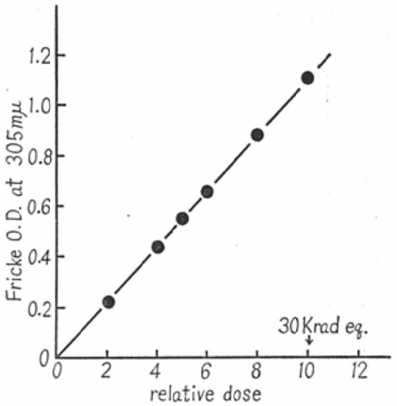
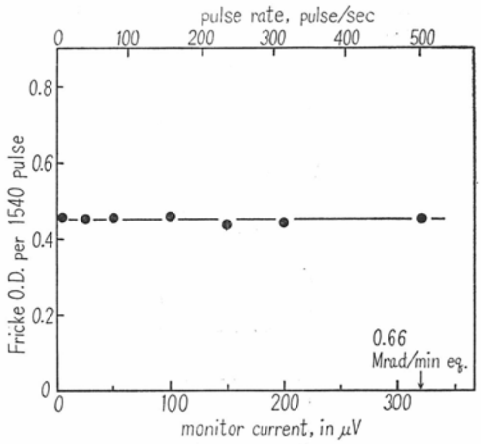



Fig. 9. Optical density of the Fricke solution irradiated with a unit integral dose of electrons, plotted against the total current to the monitor foil (0.06 mm Cu) or the pulse rate of the beam. The Fricke response is independent of the dose rate.




For the practical use, the monitor reading was calibrated against the Fricke-determined dose at various conditions for the treatment of patients or the irradiation of biological samples (see Table 1). For the patient treatment, the dose rate delivered to the skin is desirable to be controlled at several hundred rads per minute. This condition was obtained by adjusting following factors, i.e., pulse rate of the beam, distance between the accelerator head and the object, and field width. As seen in Table 1, when these three factors were fixed the monitor reading corresponded to a certain amount of absorbed dose rate in the irradiated object. The dose rate measured by Simplex Universal Dosimeter was also added in the table for reference. The difference between the Fricke and Simplex readings is considered due to the difference in geometery of the dosimeter. Since the geometery of the Fricke solution is adjustable to any kind of shape and the Simplex dosimeter cannot be applied at the high dose rate, the Fricke values were preferred here.

In biological experiment such as inactivation of the transforming activity of dry DNA by electron irradiation, the high dose rate of the order of Mrads per minute is often required. With the pulse rate 500 pulse/sec and at the nearest position, the dose rate 0.66 Mrad/min was obtained (see Table 1). The dose rate was further raised by 15% without the copper foil of the monitor.

**Automatic switch-off**

Further desirable improvement was to operate the integral dose meter and to trigger the shut-off switch when the irradiation with the desired dose is completed. Combination of the amplifier and other units to fulfill this requirement was described in the foregoing section (see Figure 6). With this device the integral current recorder was operated with a small amount of input current absorbed by the monitor foil. With the minimum detectable current, 1 $\mu$V reading on the galvanometer, the integral current recorder gave 22 count/min. This count responded linearly to the galvanometer reading. The recorder count was calibrated against the actual absorbed dose as determined by the simultaneous dosimetry with the Fricke solution. The recorder was connected with the trigger circuit for the shut-off control. Thus it was made possible to shut off the switch automatically after the pre-set dose indicated on the integral current recorder was delivered. A further improvement may be possible so that the pre-set reading itself provides an actual numerical value of the absorbed dose in the unit of rad.

**Beam centering**

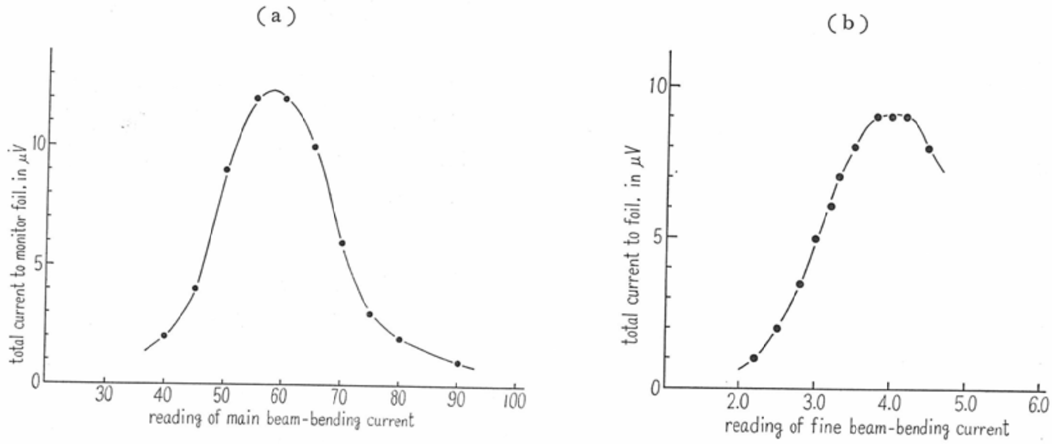
a) measurement of the total current in the electron-absorbing foil at various current of the bending magnet.

The horizontally ejected electron beam was bent at the vertical direction by two magnets in the accelerator head as indicated in Figure 4. Centering of the beam was adjusted by these two magnets. The centering as determined by the intensity of the total electron current given to the electron-absorbing foil was observed for various current provided to two bending magnets. The experimental set-up for the measurement is shown in Figure 5a. The results are shown in Figures 10a and 10b, where the total current to the foil was plotted against the reading of the beam-bending current. A pulse rate of the beam was fixed at 100 pulse/sec and a 0.1 ml thick aluminum foil was used for the electron absorbing unit during this series of experiment. It is seen in Fig. 10a that the maximum absorbed current was obtained at the reading 60 for the main bending current when the fine beam-bending current was fixed at the reading 4.0, i.e., the beam axis was directed at the center of irradiated field at the reading 60. In Figure 10b, on the other hand, the total absorbed current was plotted against vaious readings of the fine bending current, where the main bending current was fixed at the reading 60. The best centering was obtained at the reading 4.0 for the fine bending current.

b) measurement of the balance current

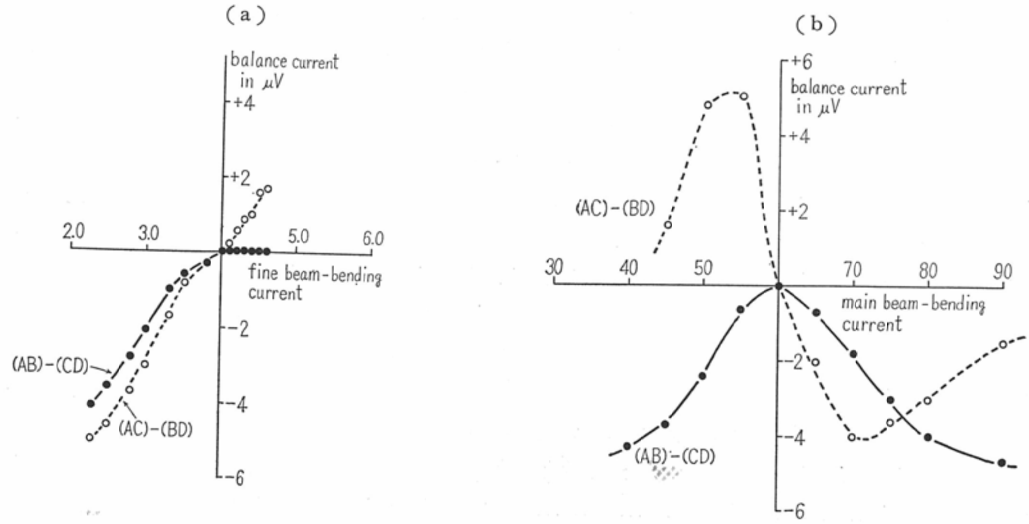
A further investigation of the beam centering was performed by measuring the balance of the fractional currents given to each of divided foils of the electron-absorbing unit. The out-puts from two foils

Fig. 10a and 10b. The reading of total current to the monitor foil (0.1 mm Al) plotted against various main beam-bending current to the magnet with fixed fine bending current (a) and plotted against various fine bending current with fixed main bending current. (b).




were respectively connected to the galvanometer (VN-11) as shown in Figure 5b. The direction of the foil separation was parallel or perpendicular to the direction of the electron acceleration. Thus the balance current between foils (AB) and (CD), or (AC) and (BD), was respectively measured. Figure 11a shows the balance current plotted against various readings of the fine beam-bending current for the fixed main bending current at the reading 60. Zero balance current means that the electron beam intensity is equally divided in two parts and consequently that the beam axis is collimated at the middle line of irradiated field. The best centering was obtained at the reading 4.0 for the fine bending current. Since

Fig. 11a and 11b. Balance current between foils (0.1 mm Al) divided along two orthogonal directions. The fine bending current was varied while the main bending current was fixed (a). The main bending current was varied while the fine bending current was fixed (b).



the beam was bent in the plane including the (AC)–(BD) direction, i.e., the direction of acceleration, the balance current was expected to change along the (AC)–(BD) direction only. However, with the fine bending current reading between 2.0 and 4.0 the beam was deflected to the (AB)–(CD) direction also, i.e., lateral to the acceleration direction. This is thought due to the internal structure of the bending magnet.

Figure 11b shows results of a similar measurement as described above with changing the main beam-bending current for the fixed reading of the fine bending current at 4.0. Zero balance current was obtained at the reading 60 for the main bending current. Peaks appearing for the (AC)–(BD) balance current are interpreted so that the beam axis was directed on the foil AC or BD with respective bending current. For the (AB)–(CD) balance current, the deflection of the beam to this lateral direction was again observed. The beam axis, however, reached the center of irradiated field at the reading 60 for the main bending current.

The centering of the electron beam was thus determined by the beam monitor, where the best centering of the electron beam in the irradiated field was obtained with the main beam-bending current at the reading 60 and the fine beam-bending current at the reading 4.0. A further modification of the monitor enables us to perform three kinds of measurement simultaneously, i.e., measurement of the dose rate, measurement of the integral dose, and control of the beam-centering. These capabilities satisfactorily fulfill the requirements for the beam-monitoring in the medical application of high energy electrons which will become more important in the future.

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