# STUDY OF GENERAL ION RECOMBINATION FOR BEAM MONITOR USED IN PARTICLE RADIOTHERAPY

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*Abstract*

For particle radiotherapy, accurate dose measurement using a beam monitor of an ionization chamber (IC) is essential to control prescribed dose to a tumor. General ion recombination is one of the most impact factors on the accurate dose measurement. The Boag theory predicts the general ion recombination effect on ionization current under the condition that ions are uniformly generated throughout the gas volume. For the particle radiotherapy using a pencil beam scanning system, however, the ions generated by the pencil beam is not uniform. We have developed a calculation code for accurate prediction of the general ion recombination effect for the pencil beam scanning system. The calculation code is called as division calculation method. The division calculation method takes into account the different ionized charge density in the beam irradiation area by dividing the ionization distribution into many sub-elements. The general ion recombination effect in each sub-element is calculated by the Boag theory. The calculation accuracy was verified by comparison of the saturation curve, which is the curve of applied voltage versus measured current, between measurements and calculation results. We measured the saturation curves by using a parallel plate IC and a cylindrical IC. We confirmed that the calculated saturation curves were good agreement with the measured curves. The division calculation method is effective tool to accurately predict the saturation curve for the pencil beam scanning system.

## INTRODUCTION

Carbon ion radiotherapy has been attracted for a cancer treatment due to the characteristic depth-dose distribution with Bragg peak. Dose localization at the Bragg peak is utilized for concentrated irradiation to a tumor. To optimize dose distribution in the tumor, a 3D pencil beam scanning system [1, 2] has been developed at the new treatment research facility in National Institute of Radiological Sciences (NIRS) [3]. The pencil beam scanning system scans the pencil beam laterally by two scanning magnets and longitudinally by variable energy changes and using range shifters. Main and sub flux monitors of an ionization chamber (IC) are also used to control prescribed dose to the tumor. Since the discrepancy between the prescribed dose and the irradiated dose leads to the worse treatment results, accurate dose measurement in the flux monitors is essential.

General ion recombination is one of the most impact factors on the accurate dose measurement. The saturation curve, which is the curve of applied voltage versus measured current, represents the reduction rate of the collected ions with reducing the applied voltage due to the general ion recombination. Accurate prediction of the saturation curve is important to design the proper specifications of the IC such as applied voltage, gap length and kind of gas to obtain the saturation current.

We can predict the saturation curve by Boag theory [4-6]. The Boag theory assumed that ions are uniformly generated throughout the gas volume in the IC. However, the ionized charge distribution generated by the pencil beam is not uniform and the distribution is modeled by the 2-dimensional Gaussian form.

In this paper, we present a calculation method giving the accurate saturation curve for ions generated by the pencil beam.

## MATERIALS AND METHODS

### *Calculation Methods*

For a parallel plate IC, the Boag theory gives an ion collection efficiency $f$ at an applied voltage $V$ [V] by following formulae:

$$f = \frac{1}{1+\frac{\xi^2}{6}} \tag{1}$$

$$\xi = 2.01 \times 10^7 \left( \frac{d^2 \sqrt{q}}{V} \right) \tag{2}$$

where $d$ [m] is the gap length between the electrodes of the IC and $q$ [C m$^{-3}$ s$^{-1}$] is ionized charge density per a unit of time. Since the ion collection efficiency $f$ depends on the ionized charge density $q$, accurate estimation of the

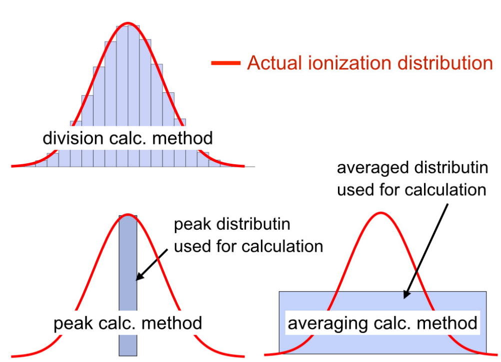


Figure 1: The different calculation methods to estimate the ionized charge distribution generated by the pencil beam irradiation.



ISBN 978-3-95450-141-0

$q$ is important. According to the Boag theory, the ionized charge density of the 2-dimensional Gaussian form is averaged in the range of the beam irradiation area. We call this calculation method "averaging calculation method". However, the averaging method does not take into account the different charge density within the beam irradiation area. Thus it is expected that the averaging method underestimates the applied voltage required to obtain the saturation current. It is undesirable because the IC designed by using the averaging method does not obtain the saturation current due to the insufficient applied voltage.

Taking the highest charge density around the beam center is the most safety method to determine the applied voltage for obtaining the saturation current. We call this calculation method "peak calculation method". However the peak method overestimates the applied voltage required to obtain the saturation current. It complicates the design of the IC due to the unnecessary high-applied voltage.

To calculate the saturation curve for the actual ionized charge density, we divided the ionization distribution of the 2-dimensional Gaussian into many sub-elements and assumed that the charge density in the each sub-element is uniform. We calculated the saturation curve for ions in the each sub-element by using the Boag theory. Then the saturation curve of the ions in the whole irradiation area was obtained by weighted average of the saturation curves in the each sub-element. We call this calculation method "division calculation method". The conceptual schemes of the three calculation methods are represented in Figure 1.

In the averaging calculation method, we defined the beam irradiation area as a circle with the radius of 3 $\sigma$ of the pencil beam. In the division calculation method, we divided the beam irradiation area of the circle into sub-element with area of $0.1 \times 0.1$ mm$^2$. The peak calculation method used the ionized charge density in the sub-element at the beam center for the calculation.

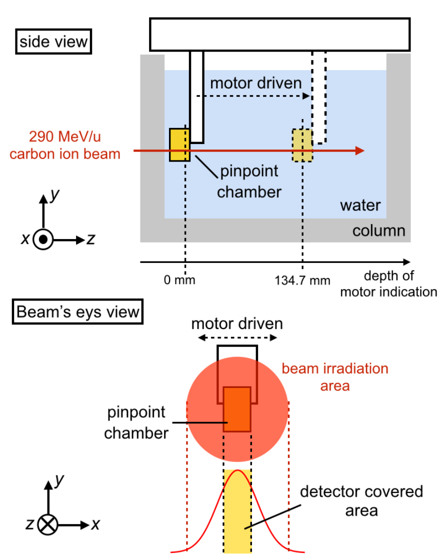


Figure 2: Experimental arrangement using a cylindrical pinpoint ionization chamber.

## *Experimental Arrangement*

The saturation curves calculated by the three different calculation methods were compered with those measured by using two types of IC: a parallel plate IC and a cylindrical IC. The measurements were repeated three times in a single condition and compared the average value with the calculation results.

**Parallel Plate Ionization Chamber (PPIC)**, the purpose of this experiment was verification of the calculation accuracy of the division calculation method by comparison of the saturation curve obtained by the measurement and by other the two calculation methods. We used a parallel plane ionization chamber (PPIC). The PPIC design was the same of the existing flux monitors [3]. The PPIC consisted of an anode of signal foil and two cathodes of wire mesh. The gap between the anode and each cathode was 5 mm. The PPIC was operated in air at atmospheric pressure. We used carbon ion beam with 430 MeV/u extracted from Heavy Ion Medical Accelerator in Chiba (HIMAC) and irradiated the pencil beam to the PPIC. We measured the saturation curves with the different beam intensities in the range of applied voltage from -100 V to -2,800 V. The beam intensities of $4.6\times10^7$, $2.8\times10^8$, $4.1\times10^8$ and $8.3\times10^8$ particles per second (pps) were used. The pencil beam was modeled to the Gaussian with 2 mm rms for the calculations.

**Cylindrical Pinpoint Ionization Chamber (CPIC)**, the calculation accuracy of the division method was verified more in detail. We measured a part of the ionized charge in the irradiation area of the pencil beam by using a cylindrical pinpoint IC (CPIC) developed by PTW Freiburg GmbH (PTW 31015). The experimental arrangement using the CPIC is shown in Figure 2. We defined that the beam direction is $z$-direction and the $x$-$y$ plane is the perpendicular plane to the $z$-direction. The lateral size of the CPIC was smaller than the lateral beam spread of the pencil beam. The center position of the CPIC was arranged at $(x, y) = (0, 0)$ mm corresponding to the beam center in water. We moved the chamber location in the $z$-direction by using a motor drive unit and the saturation curves were measured at the motor indicated depth of 0 and 134.7 mm. The depth of 134.7 mm was estimated at the depth corresponding to the depth of the Bragg peak. Then we also drove the chamber location in $x$-direction from 0 to 10 mm at the each depth and measured the saturation curve at each lateral position. We used the pencil beam of carbon ion with 290 MeV/u and measured the saturation curve in the range of applied voltage from 40 to 400 V.

We calculated the ion collection efficiency in the CPIC by using equation (1) and (2). For a cylindrical chamber, $d$ in the equation (2) is obtained by following formulae:



ISBN 978-3-95450-141-0

$$d = (a - b)K_{cyl} \tag{3}$$

$$K_{cyl} = \sqrt{\frac{(a/b+1)}{a/b-1}\frac{\ln(a/b)}{2}} \tag{4}$$

where $a$ is the radius of the outer electrode and $b$ is the radius of the central electrode. For the CPIC we used, $a$ and $b$ were assigned with 0.15 mm and 1.45 mm, respectively. The size of the lateral beam spread was 2.2 mm rms at the depth of 0 mm and 2.6 mm rms at the depth of 134.7 mm.

## RESULTS AND DISCUSSIONS

### *Parallel Plate Ionization Chamber*

The Figure 3 (a) and (b) are the comparisons of the measured saturation curves with the curves calculated by the three calculation methods. The Figure 3 (a) is the comparisons for the beam intensity of $2.8\times10^8$ pps, and Figure 3 (b) is the comparisons for the beam intensity of $8.3\times10^8$ pps. The small lower right graphs in the both Figures 3 (a) and (b) are close-ups in the curve rising region. The saturation curves are normalized by the value at the applied voltage of 2500 V. Since uncertainty of the measurements is estimated to be within 0.1% rms and the error bar is smaller than the maker size, the error bars are not displayed in the Figure 3.

We confirmed that the saturation curves calculated by the division method are the best agreement with the measured curves in the all calculated saturation curves.

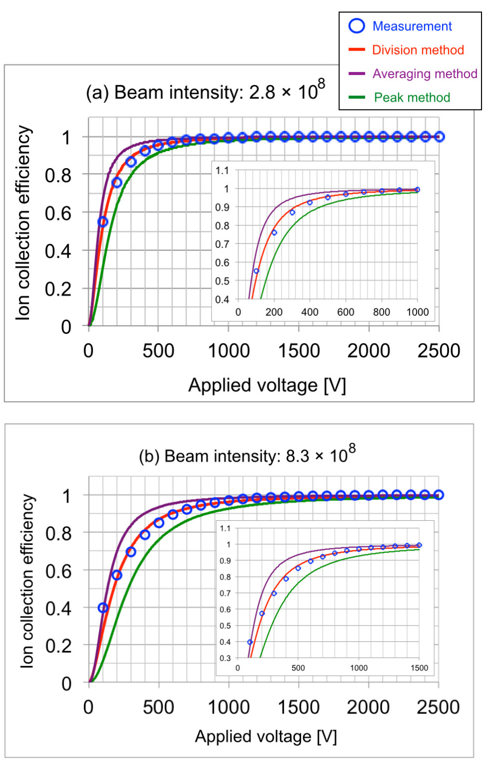


Figure 3: Comparisons of the saturation curves between measurements and calculation results obtained by using different calculation methods for the parallel plate ionization chamber.

We also found that the applied voltage reaching to the saturation level is different depended on the calculation methods. The difference of the applied voltage was attributed to the different ionized charge density used by each calculation method. Then the difference observed for high intensity beam irradiation was larger than that observed for low intensity beam irradiation. It indicates that the division method is more effective when the beam intensity is higher.

### *Cylindrical Pinpoint Ionization Chamber*

Figure 4 is the comparison of the saturation curves between measurements and calculation results of the division method at different depths in water. The Figure 4 (a) and (b) are the comparisons of the saturation curves when the lateral center position of the CPIC is $(x, y) = (0, 0)$ mm and (5, 0) mm, respectively. The error bar of measurements corresponds to the 2 times the rms error. The saturation curves are normalized by the averaged value between the applied voltage of 250 V and 400 V.

When the CPIC was located at the beam center, the saturation curves calculated by the division method were good agreement with measured curves (Figure 4 (a)). In contrast, when the CPIC was located at off beam axis, some discrepancies were observed even in the saturation region (Figure 4 (b)). In addition, the Figure 4 (b) indicated that the ion collection efficiencies measured at depth of 0 mm around the low applied voltages region are higher than the efficiencies in the saturation region.

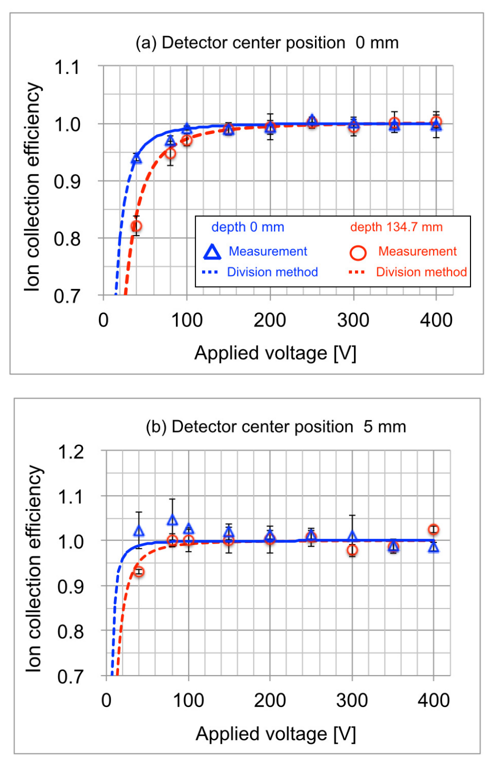


Figure 4: Comparisons of the saturation curves between measurements and calculation results obtained by using the division method for the cylindrical pinpoint ionization chamber.



ISBN 978-3-95450-141-0

It is possible that the misalignment of the detector center position caused the inexplicable measured saturation curve. When the detector was located at $x$ = 5 mm, the detector covered a part of penumbra region of the Gaussian and the ion collection efficiency can sensitively varied with the slight variation of the detector center position. Then we estimated the influence of the variation of the detector center position on the saturation curve. In the division calculation method, we shifted the detector center position between ($x$, $y$)=(±0.3, 0) mm with a sampling pith of 0.1 mm and calculated the saturation curve at each lateral position. Figure 5 is the same comparison of the saturation curve represented by the Figure 4 (b). The comparisons at $z$ = 0 mm and 134.7 mm in the Figure 4 (b) are separated to the Figure 5 (a) and (b), respectively. The error bar indicates the variation range of the measured value with variation of $x$ =±0.1 mm of the detector center position. With the variation of the detector center position between $x$ = 0.1 mm and -0.1 mm, the measurement results varied about ±6～9%. The calculated saturation curves were consistent with the measured curves including the misalignment of the detector center position with $x$ = ±0.1.

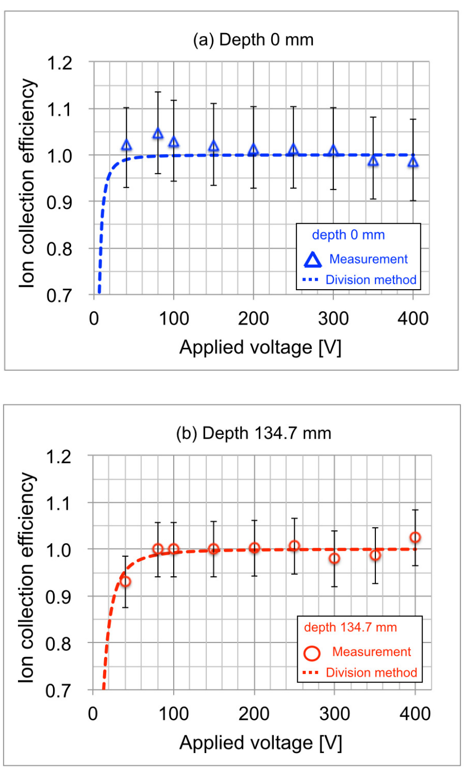


Figure 5: Comparisons of the saturation curves between measurements with the position error and calculation results obtained by using the division method. This is the same comparison represented by the Figure 4 (b). The error bar indicates the variation rage with variation of the detector center position with ($x$, $y$) = (±0.1, 0.0) mm.

## CONCLUSIONS

We have developed the division calculation method to accurately calculate the saturation curve for a pencil beam scanning system. We confirmed that the saturation curves calculated by the division method are good agreement with those measured by the PPIC. We also verified in detail the calculation accuracy of the division method by comparing with the saturation curves measured by the CPIC. We found that the calculated saturation curves are consistent with measured curves including the misalignment of the detector center position. The division method is effective tool to calculate the general ion recombination effect on the measured current for the pencil beam scanning system.

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ISBN 978-3-95450-141-0