An online monitor ionization chamber used in particle therapy

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Abstract The clinical trials of tumor therapy using heavy ions beam ^{12}C are now in progress at Institute of Modern Physics in Lanzhou. In order to achieve the precise radiotherapy with the high energy ^{12}C beam in active pencil beam scanning mode, we have developed an ionization chamber(IC) as an online monitor for beam intensity and also a dosimeter after calibration. Through the choosing of working gas and voltage, optimizing of the electrics and the read-out system, calibrating the linearity, the detector system provide us one of the simple and highly reliable way to monitoring the beam during the active pencil beam scanning treatments. The measurement results of this detector system show that it could work well under the condition of high energy ^{12}C beam in active pencil beam scanning mode.

Key words Heavy ion beam therapy, Integral ionization chamber, Irradiation dose, Absorb dose

1 Introduction

Heavy ion beams have been used for medical purposes since early 1950s [1]. Because of the Bragg peak in dose distributions of the ions, the healthy tissues received much lower doses than the region defined by spread-out Bragg peaks (SOBPs). Particle therapy (PT) facilities in operation include HIMAC (Japan) and GSI (Germany)[2]. Other facilities are in construction in Italy (TERA)[3], Germany (Heidelberg)[4] and so on. Referring to the clinical cases of PT[5], it is evident that good localized tumor control and high patient survival rates have been achieved by heavy ion treatment without side effect or with tolerably acute toxicity. Accordingly, carbon ion therapy has been recognized as a promising modality against tumors in the community of radiation therapy. A facility for treatment of localized skin-seated tumors has been installed at Institute of Modern Physics (IMP) in Lanzhou[6]. Sixty-six patients have been treated with 100 MeV/u beam in the PT terminal since November 2006.

A pencil beam system for treatments of deep-seated tumor has been in progress at IMP. Being different from the passive beam system, the pencil beam should be up to 430 MeV/u, with beam intensity of up to 1.0×10^8 s^{-1}, which cannot be tolerated by the scintillator for beam intensity monitoring. As shown in Fig.1, where the scintillator counts vary with the beam intensity (read by a standard ionization chamber), for beam intensity of > 3.5×10^6 s^{-1}, pileup of the scintillator pulses causes obvious decrease of the detection efficiency.

An ionization chamber (IC) has been developed at IMP for monitoring heavy ion beams of large intensities. It has the following advantages:

(1) Large dynamical range of possible counting rates. There are two operating modes for high precision readout of the ionization chamber: event-by-event readout mode under beam rates of 10^4~1 s^{-1} and the integral mode under beam rates of 10^4~10^8 s^{-1} for an active pencil beam raster scan delivery system.

Supported by the National Nature Science Foundation of China (No. 10305015, No.10475098) and the Major Program of the Chinese Academy of Science (No. O701050YZD)

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Received date: 2008-11-21

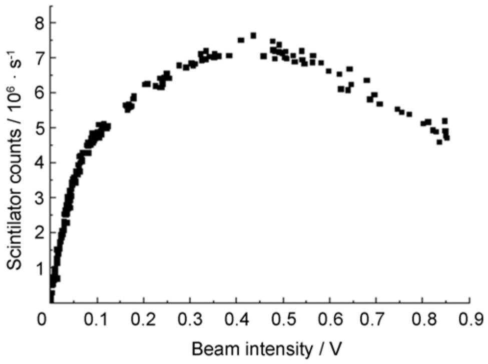

Fig. 1 Scintillator count vs. beam intensity. Non-linearity is observed when the beam intensity exceeds 3.5×10^6 s^{-1}.

(2) A calibrated IC can be a standard instrument for clinical dose measurements on time. In a passive beam shaping system, the translating coefficient between the scintillator counts and the absolute irradiation dose can be measured before the treatments. And the irradiation dose is proportional to the output of the scintillator monitoring the beam during the treatment.

(3) Energy loss of the heavy ions in the IC is negligible.

(4) Small background of the IC using novel electronics and data analyzing system[6]. Its long term stability, direct readout, and relative ease of use, allow it use as beam intensity monitor and dosimeter. And it is handy enough for pencil beam applications.

2 Technical description

2.1 Framework of the detector

The ionization chanber consists of two windows, the anode and cathode, in active area of 100 mm ×100 mm. The anode and cathode are made of 1.5-μm gold-filled Mylar foils. The collection gas gap is changeable. The two electrodes are included in a pair of 7-μm Kapton windows, which connect the ground for compensating an eventual variation caused by relative electrical attraction of the internal electrodes. The working gas flows between the external windows and the electrodes in order to increase the detector gain and keep the pressure constant.

2.2 Read-out electronics

NI-PXI-6133 (PC based DAQ system) is used as read-out electronics of the detector for simultaneous sampling with an adjustable 20 MHz clock. Output charge of the IC in integral mode can be several nC/s to tens of μC/s. Through a 66 MΩ resistance, which convert the current into a voltage (0 ~10 V), the output is send as the input of PXI6133, which samples 200 000 times per second. The LabVIEW was used for data analysis and display, and for sending trigger signal to the control catenation devices according to the beam condition and therapy plan [7]. Fourier transform of the signals from the data acquisition system is performed by the Advanced Signal Processing Toolkit of LabVIEW, reducing the background of IC to < 0.1 mV. In other words, the background current is 0.1 mV/66 MΩ ≈1.5 pC/s which means a relative error of 1.2 ‰, over 10 times better than the minimum background (1.7%) of the IC detector at GSI. Fig.2 shows the output of IC analyzed under LabVIEW in a therapy. Each peak presents an irradiation of a slice of tumor.

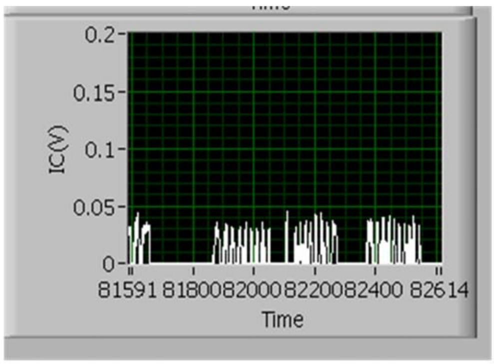

Fig.2 The output of IC analyzed by LabVIEW during the therapy.

3 Results

The data were collected to get basic information about performance of the chamber, and to validate beam energy and dose distribution of the radiation fields. The collecting gas gap of the detector was fixed at 6 mm and N_2 was chosen as the best working gas for the IC, comparing with other gas of 90%Ar +10%CH_4, He, Ar, air, and 80%Ar +20%CO_2. The initial test was done in atmosphere, so as to compare output of the IC with that of the PMT23342 dosimeter working in atmosphere, too.

Linearity of the detector and the Bragg peak position, which reflects the beam energy, are discussed in this section. The irradiation dose and the delivered dose are compared with the results of the PTM23343 dosimeter.

3.1 The linearity

Recombination of the ions and ion-induced electrons increases with the beam intensity. This reduces the collected charge in the detector and affects the dose measurement. So output of the IC should be linear under beam intensity of 0~10^8 s^{-1} for reliable results of the measurement.

For beam intensities of up to 10^8 s^{-1}, linearity of the IC was checked with the PTW23343 detector, a plate integral ionization chamber that is commercially available and works for irradiation doses of up to 100 Gy with a linearity of better than 99%. In Fig. 3, outputs of the ionization chambers under beam intensity of up to 10^8 s^{-1} are plotted against the PTW23343 output. Deviation of the two data sets is less than 1%. This fulfills the requirement for the heavy ion beam treatment.

3.2 The Bragg peak

By increasing thickness of PMMAs placed in front of the detector, we can measure the transverse beam spread as the beam energy decreases. Two configurations of the absorbers were used for the measurement: with PMMAs of different thicknesses, and an aluminum ridge filter instead of the PMMAs. The results of Configuration 1 are plotted in Fig. 4 (a), where the PMMA thicknesses were converted into water equivalent depths. The Bragg peak of 100 MeV/u ^{12}C beam is positioned at 24.1 mm. The experimental data (full squares) and simulation results (the solid line) agree well with each other. With Configuration 2, because of multiple scattering of the ^{12}C ions by the ridge filter, the Bragg peak was broadened (Fig. 4b) to 3.5 mm (FWHM) from 1.5 mm of the case of Configuration 1. This peak-broadening effect ensures the beam to overlay the dose over the whole volume of the tumor in treatment.

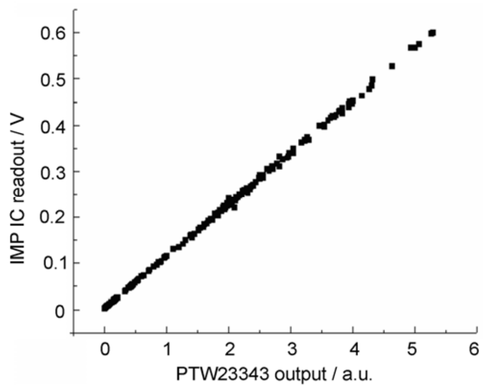

Fig. 3 Linearity of IC working in integral mode.

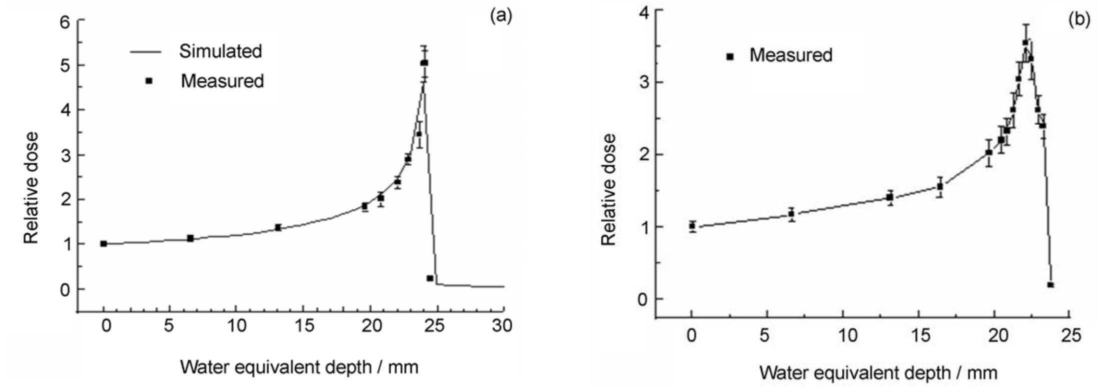

Fig. 4 Bragg peak reconstruction under two configuration.

3.3 The dose measurement

It is assumed that energy loss of the ions in the working material of the detector is negligible, and no nuclear reactions take place in the treatment condition. When the energy spread is small in the working volume of the detector, the irradiation dose in Gy can be written as[8]

$$D = \Phi(S(\bar{E})/\rho) = \left(\frac{N}{\alpha}(S(\bar{E})/\rho)\right) \times 1.602 \times 10^{-10} \tag{1}$$

where $S(\overline{E})$ is the stopping power at the average energy (E), Φ is the total number of particles per unit area of the beam passing through the absorber, N is the number of primary particles, α is the effective area of beam profile, which is smaller than the working area of IC. According to the collecting charge Q measured from IC, which is proportional to N, the irradiation dose D can be calculated. Then the absorbed dose D_m can be written as[8]

$$D_{\rm m} = K_Q N_{Dw} D \qquad (2)$$

where K_Q is correction factor for the effects of the difference between the reference beam (^{60}Co γ-rays) and the ion beam, N_{Dw} is the calibration factor in terms of absorbed dose to water for ^{60}Co.

In our case, uncertainty of the dose measurement comes from not only the statistical errors, but also the following effects: ion-electron recombination that affects the collected charge; homogeneity of the collecting field in the active gas volume of the IC (according to measurements at GSI, the difference of charge collection between outer border and the center could be up to 80%[9]); some correction factors for what we considered as constants (e.g. the stopping power S, which depends on the particle species and energy, and particular treatment plan, has an uncertainty of 1%; and the $N_{\rm Dw}$, which is dominated by the water to air stopping-power ratio, has a variation of over 3% in clinical beams[10]); and conditions of the treatment plan.

According to the propagation of errors, the uncertainty of the measured dose D_m is about 15%. The difference between the doses measured by PTM23343 and by the Integral IC we developed is within the range of the error as we expected.

4 Conclusion

Heavy ion beam therapy requires a precise detector to monitor the beam intensity and the dose irradiation on the tumor. This integral IC we developed have the following characters: the background is less than 0.1 mV; the high collection efficiency with an electric field of 400 V; direct read-out of the beam intensity and the dose with the LabView program. It could be served as online monitor and dosimeter very well after calibration by the standard detectors.

The full system including the detector, read-out, and the processor provide us one of the simple and highly reliable ways to monitoring the beam during the active pencil beam scanning treatments.

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