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PHYSICAL STUDIES OF BEAM DELIVERY SYSTEM FOR PROTON AND HEAVY ION TREATMENT

Akio Higashi, Tatsuaki Kanai*, Hiromi Tomura*, Masahiro Endo*, Akifumi Itano, Hiroshi Karashima and Yoshio Hishikawa

Charged Particle Treatment, Public Health and Environment Department, Hyogo Prefectural Government, Kobe, Hyogo, Japan
*Research Center of Charged Particle Therapy, National Institute of Radiological Sciences, Chiba, Japan

Abstract

We report design and optimization of beam delivery system for proton and heavy ion particles, which will be constructed in charged particle therapy facility in Hyogo Prefecture. Penumbra sizes were calculated for different systems to optimize device parameters under considering effects of multiple scattering and energy loss of beam. It was found that penumbra size of carbon ion beam was about three times smaller than that of proton, and that devices which affect physically in particle delivery system should be placed as upstream as possible to reduce penumbra size.

1. Introduction

It is reported here the results of physical investigation for beam delivery system using proton and heavy ion beam to construct facility of charged particle therapy in Hyogo Prefecture. In this facility, the three fixed beam ports which deliver proton and heavy ion (helium and carbon) beam and a rotatable gantry using proton are planned for treatment issue. The beam delivery system which include such beam ports and gantry have not yet been constructed in Japan.

In the design of the beam delivery system, important devices are wobbler magnets, scatterers, ridge filters and range shifters, because they scatter beam particles and affect penumbra size. Position of these devices are investigated, assuming sizes of the devices which are slightly different from those used in Heavy Ion Medical Accelerator in Chiba (HIMAC) in National Institute of Radiological Sciences (NIRS) but structures of them are almost same as those in HIMAC. Penumbra of the delivery systems which were designed under specification were calculated. Since it is necessary for accurate treatment that penumbra are to be as small as possible, the goal of their size is about 2 mm.

2. Design of the beam delivery system and calculation for penumbra designed

In calculating penumbra, the method developed in NIRS was employed. Physical meaning of the calculation is as follows[1]. Particle distribution is obtained as an approximated solution of the Boltzmann equation. In this case, multiple scattering and energy loss are assumed when particles pass through material in the devices of the delivery system. Fermi and Eyges showed that radial deflection y and its angle ϕ of the particles passing through materials under those assumptions could be calculated[2]. At the formulation, the quantity D which corresponds to the emittance squared in the beam transport are to be written as

$$D = \langle y^2\rangle \langle\phi^2\rangle - \langle y\phi\rangle^2,$$

where $\langle y^2\rangle$ and $\langle\phi^2\rangle$ are the variances of y and ϕ, respectively and $\langle y\phi\rangle$ is cross term. It is important that effects of multiple scattering and energy loss are already included in them. D is calculated by $\langle y^2\rangle$, $\langle\phi^2\rangle$ and $\langle y\phi\rangle$ which are values on the material at each grid point segmented small enough along the beam direction. Penumbra $P_{80\to20}$ are to be written as follows;

$$P_{80\to20} = 1.68\ \sigma_\phi L_c,$$
$$\sigma_\phi^2 = D/\langle y^2\rangle + \langle y^2\rangle\ (\ \langle y\phi\rangle/\langle y^2\rangle - 1/L_w\ )^2,$$

where L_c and L_w are the distances from isocenter to collimator and wobbler magnet, respectively. Here the quantitative definition of the penumbra is the distance between 80 % dose point compared to the dose of isocenter and 20 % point of that on lateral dose distribution. This calculation method have much advantage for its analytically solved results than the usually used Monte-Carlo method, because it is easy to understand about the effect of positions of the devices and materials and takes much less times to calculate. For example of position of the devices, it is important to place a collimator to a patient body as close as possible. The results of this method for beam delivery systems in HIMAC have been found to agree within 1 mm or less, which is about 10 % of the penumbra size measured by X-ray photograph.

Figure 1 shows an example of fixed beam port used for proton and heavy ion beam. Calculations for this system were made for 165 and 230 MeV energies of proton and 320 MeV/u energy of carbon ion beam. Figure 2 shows an example of rotatable gantry for proton only. Calculations for this gantry were made for 165 MeV energy of proton beam. Maximum range of each kind of beam through these delivery systems are about 17 cm for both 320 MeV/u carbon ion and 165 MeV proton beam and about 30 cm for 230 MeV proton, respectively. Distance, L_c, between collimator and isocenter was set to be 40 cm.

3. Results and discussions

Firstly, for the fixed beam delivery system shown in the Figure 1, field radius, maximum range and spread out Bragg Peak (SOBP) width were set to be same in carbon ion and proton beam. The maximum range and SOBP width were taken as 17 cm mentioned above and 6 cm, respectively. Dependence of penumbra size on field radius which was adjusted by scatterer thickness and radius of wobbler were estimated. It was found that the dependence was small but the absolute value of penumbra in the case of proton beam were about three times larger than those of carbon ion beam in the same range. The results are shown in Figure 3. It was also demonstrated that the heavier ion, such as carbon, can perform more accurate treatment.

In next step, effects of scattering in compensator and inside of a patient body were estimated. For simple studies, water was placed after a collimator and its thickness was changed. Water is often used in estimation of scattering in compensator and human body, because density of water is almost the same as polyethylene which is the material of compensator and as a human body. Figure 4 shows the dependence of penumbra size on water thickness in this calculation. It was found that the size of penumbra caused by scattering in the body was smaller than that by the delivery system. It was also shown that the effect of scattering in the compensator was much smaller than that in the body because of difference of path length. As is in the Figure 3, absolute penumbra size of proton beam in the Figure 4 was also found to be about three times larger than that of carbon ion.

In the last study, penumbra size was calculated by changing the position of ridge filter in the gantry shown in the Figure 2 for proton. The results are shown in Figure 5. It can be seen that the distance between scatterer and ridge filter is longer, the penumbra size is larger. The dependence of penumbra size on the positions of devices which scatter beam particles is not only for ridge filter position but also for those of scatterer and range shifter. Scatterer, ridge filter and range shifter should be placed closely each other and as upstream as possible, and the distance from range shifter to the isocenter is to be taken as long as possible. However, it is much difficult in working upon the ridge filter, because the thickness and gaps of the ridges should be much smaller. Selection for material which is easily worked upon or oscillating bar ridge filter and rotating spiral ridge filter are to be taken into account.

Three-dimensionally conformed (3-D) irradiation system is under planning in this facility, because it has much advantage for dose localization. Searching parameters of devices in beam delivery system for adjusting irradiation field can also be simplified using the 3-D system. Dynamic 3-D system without devices which scatter particles and absorb energy of the beam will be installed in this facility to use maximum range of initial beam energy and minimum penumbra size by initial emittance.

References

1) H. Tomura et al., Abstract Book of the Fifth Workshop on Heavy Charged Particles in Biology and Medicine, GSI (1995).

2) L. Eyges, Phys. Rev. **74** (1948) 1534.

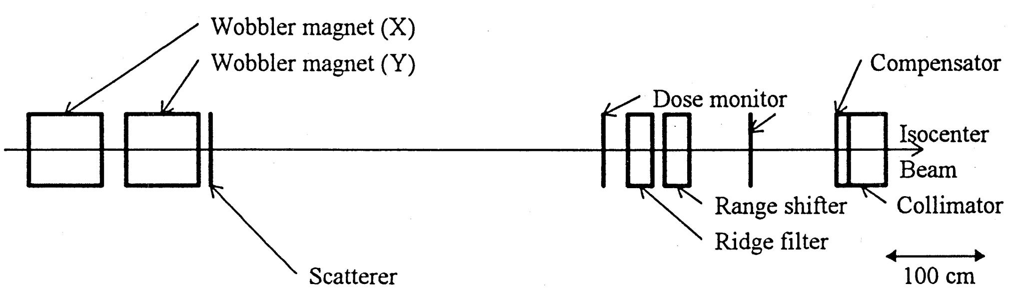

Figure 1. Fixed beam delivery system for proton and heavy ion beam . Total length shown here is 940 cm.

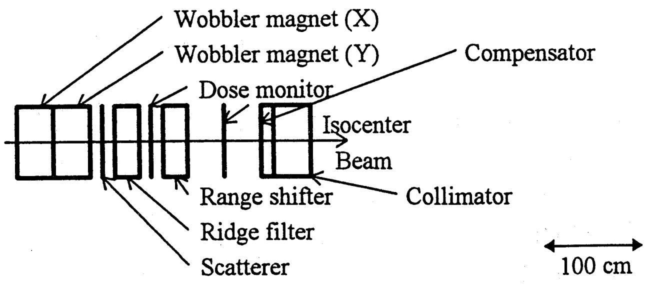

Figure 2. Rotatable gantry for proton beam . Total length shown here is 350 cm.

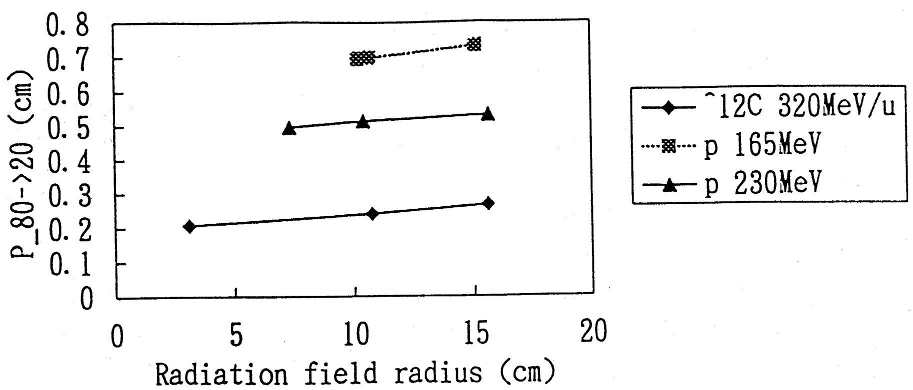

Figure 3. Dependence of penumbra size on field radius at 6 cm of SOBP width.

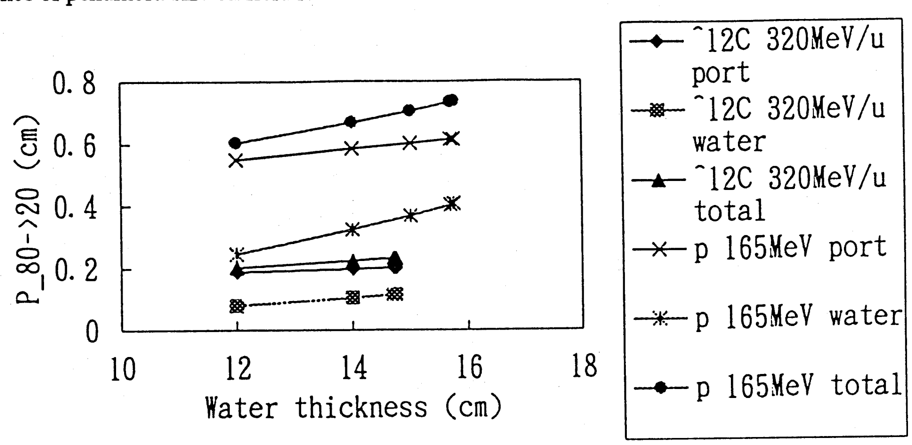

Figure 4. Dependence of penumbra size on water thickness. Water is placed downstream of collimator.

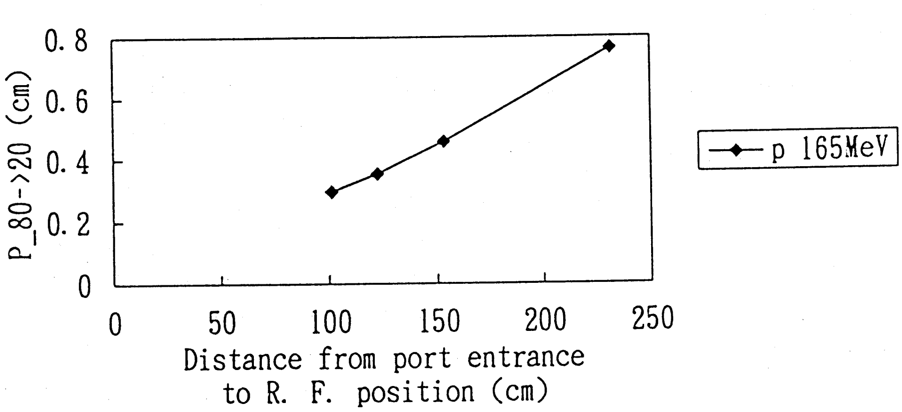

Figure 5. Dependence of penumbra size on ridge filter position in gantry for proton.