A Formation of Ion Intensity Distributions on a Target Appropriate for a Neutron Source for Boron Neutron Capture Therapy

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This paper proposes a new method of scanning beams from several radio-frequency quadrupole (RFQ) accelerators on a target, and gathering them into a bundle of ion beams on the target which is prepared for a neutron source of boron neutron capture therapy(BNCT). The scanning apparatus is composed of a solenoid coil and wobbling magnets. The method will be found to produce various forms of ion intensity distributions on the target, and as a result, to provide the neutron source with favorite neutron flux distributions for BNCT.

Key Words: boron neutron capture therapy, BNCT, RFQ, proton, neutron generator

1. Introduction

Boron Neutron Capture Therapy(BNCT) which uses neutrons produced in fission reactors has been motivated by the desire to find an alternative therapy for malignancies where conventional radiation therapies fail, such as glioblastoma multiforme(GBM), a malignant brain tumor, and nowadays is playing a part as one of radiotherapy.⁽¹⁾ In spite of that, as reactors are too expensive, it is found to be very difficult to construct one used only for BNCT. And then, at the First and Second International Conference on BNCT, a number of accelerator-based neutron sources for BNCT were proposed and were claimed superior to reactor sources for a number of reasons.⁽²⁾⁻⁽⁴⁾ Some of the practical advantages are lower capital costs, lower operating costs, compactness, and the possibility of siting in hospital. One of the physical advantages claimed is a better neutron energy spectrum with less contamination by gamma rays.⁽²⁾

One proposed as neutron sources uses electrostatic accelerators^{(1),(4)}, and another uses a radio-frequency quadrupole (RFQ)⁽³⁾ or a DC electrostatic quadrupole⁽⁶⁾ accelerator, as main accelerators. Neutron sources using ^{252}Cf are distributed, too.

In this paper where a RFQ-based neutron source is adopted, is proposed a new method of scanning ion beams from several RFQs on a target, and gathering them into a bundle of beams on the target which is prepared for the neutron source for BNCT. The scanning apparatus is composed of a solenoid coil and wobbling magnets. The method will be found to produce various forms of ion intensity distributions on the target, and as a result, to provide the neutron source with favorite neutron

distributions for BNCT.

At first, is described a constitution of the neutron source proposed in this paper. Next, ranges of neutron flux and energy required for BNCT are shown. Various kinds of neutron sources and their principle of neutron productions are simply outlined. Then some features with beam lines of this proposal are presented. Some distributions of ion beams on the target which are one of main themes of this paper, are described and their features are viewed in detail.

2. Basic constitution

In figure 1 is shown a basic constitution of the neutron source including the proposed scanning structure. It is composed of a chain of conventional apparatuses, that is, ion sources, RFQs, some quadrupole focusing and bending magnets, and a target which plays a part as a neutron production source.

Fig.1 A constitution of proposed neutron sources

In Fig.1 three beam lines, A, B and E, including a RFQ

as a main accelerator for each line are shown, and intersect at the point O of the beam entrance of the solenoid coil, and form a bundle of beams at its beam exit, and get to the target. As a matter of fact, the neutron source is composed of five beam lines of which two beam lines are not shown in Fig.1. The two beam lines, C and D have the same beam lines and components as the beam lines A and B are arranged rotating 90° angle around the axis of the beam line E.

One of the reasons why the neutron source has the five beam lines, is to obtain a strong beam current, and to result in a strong neutron flux enough to BNCT. Another reason is to obtain wider homogenous area of ion beams distributed on the target than in a beam line. The scanning method makes use of both of the solenoid coil and a wobbling magnet b1(or b2) on the beam line A (or B) shown in Fig.1.

Neutrons produced by the ion beams have far higher energies than the energies used in BNCT, and the source neutrons should be moderated by moderator assemblies and their energies should be decreased within the energy range available for BNCT. The moderator, which is coaxially aligned to enclose the target close to its lower part along the beam line, and then can accept about 80% neutrons produced at the target,⁽²⁾ will have a cylindrical form with a disk at its end as shown in Fig.1.

3. Conditions requested for the source neutron

BNCT makes use of both of α -particles and daughter nuclei, ^7Li , which are produced by the $^{10}\text{B}(n, \alpha)^7\text{Li}$ reactions. ^{10}B in that reaction are concentrated only tumors by the carrier. Their particles whose ranges are less than the cell are able to kill only the tumors without any damages of normal cells, and then they are said to provide one of the most ideal tumor treatments.⁽⁶⁾

Recently, BNCT has required a beam of neutrons which penetrates a tumor-containing brain deep enough to create an intense neutron field at the tumor site. A thermal neutron beam is unsatisfactory in this respect and efforts have been made to develop epithermal beams using reactor and accelerator.⁽⁷⁾ In a simulation with the neutron flux required for a tumor,⁽¹⁾ when the beam current and energy for the used proton accelerator are 20 mA and 2.2 MeV, respectively, the neutron thermal fluences at a depth of 8cm has about $1.2 \times 10^{12} \text{ n/cm}^2$ and then the treatment time is reported to take about 40min. The treatment time in this paper is set one tenth as much as the above time. Thus the thermal neutron intensity is required to have more than $5 \times 10^9 \text{ n/cm}^2\text{s}$ at the depth of 8cm.

4. Principles of neutron production

Neutron production methods are due to various reactions such as the $\text{T}(d,n)$ reaction, photon nucleus (γ, n) reactions, the $\text{Li}(d,n)$ or $\text{Li}(p,n)$ reaction, spallation reactions, nuclear fissions and so on.⁽⁷⁾ Their neutron yields are given by the order of spallation > fission > $\text{Li}(d,n)$ > $\text{Li}(p,n)$. The order of their produced heat amounts which should be less, is given by spallation < fission < $\text{Li}(d,n)$ < $\text{Li}(p,n)$. However the spallation which is the best reaction is applicable only to higher energy ions. In this paper the fourth reaction $\text{Li}(p,n)$ is chosen because neutrons produced by deuteron have significantly higher energies so that it is very difficult to practically obtain the high purity, high intensity epithermal beams required for BNCT.⁽⁸⁾ For the $^7\text{Li}(p,n)^7\text{Be}$ reaction for 2.2 MeV protons stopping in a thick ^7Li target,⁽⁷⁾ the total neutron yield in the current of 100mA amounts to as much as $3.4 \times 10^{13}(\text{n/s})$.

Here the neutron yield using the above result is expected to amount to $1.7 \times 10^{14}(\text{n/s})$ which result in $1.7 \times 10^{14}/4\pi(50^2)(\text{n/cm}^2\text{s}) = 5.4 \times 10^9 (\text{n/cm}^2\text{s})$. This satisfies the requirement for the neutron intensity described in Sec.3. Here the irradiation points are assumed to be located equivalently at 50cm from the target including some moderator's effect.

5. The beam scanning method.

5.1 Incident conditions into the solenoid field

The arrangement of the beam lines in this proposal is already shown in Fig.1. The scanning means is composed of both of the wobbling magnet of each beam line except E and the solenoid coil which is used in common for the four beam lines, A, B, C and D. The straight line E hasn't any wobbling magnet in the example of Fig.1 and is directly not connected with the scanning one.

Fig.2 Typical arrangement of the five beams on the target and the used (x,y) coordinate system

In Figure 2 an example of the arrangement of the five beams on the target is shown. The coordinates(X,Y,Z) are defined in fig.2 where its (X,Y) or (r, θ) plane is parallel to

the target plane. Moreover, Z axis on which the beam line E is set to fall, is normal to the figure, and the direction of the Z-axis points to its front. And the center of the target is the origin of the (X,Y) or (r,θ) plane. Each center of the beam lines is called there by the same name as that of the respective beam lines. The circle with a radius of the standard deviation σ with each gaussian intensity distribution assumed for beam cross-sections is given in the figure and also a circle with r_T in radius, which the four beam centers are on and tied by, is shown. The value r_T is corresponding to each radial position of the off-axis four beams and is equal to the medium of each gaussian distribution, μ.

Suppose the beam line A as the representative of the four beam lines. The function of the scanning apparatus is explained using that line, and also symbols used in the following description are defined in Figure 3.

The dipole magnetic field of the wobbling magnet is moderated by a frequency ω_M with time. Then an incli-

Fig.3 Main symbols used on an analysis of a charged particle motion in the solenoid magnetic field.

nation r₀' of its beam for the axis of the beam line E at the point of the intersection O is, on the deflecting plane of the wobbling magnet, given by

$$r_0' = r_A' + \Delta r_A' \sin \omega_M t \quad (1),$$

where, ' = d/dz, r_A' is the inclination of the beam line A for the beam line E without any modulation of the wobbling magnet, and Δr_A' is the amplitude of the time varying term of Eq.(1). The beam displacement from the point O on the plane normal to the beam line E at the beam entrance of the solenoid coil is given by

$$r_0 = (I \Delta r_A' / \cos r_A') \sin \omega_M t \quad (2),$$

where I is the length from the middle point of the wobbling magnet to the point O. Δr_A' and ω_M have ~5° angle and a value from 10 Hz to 100Hz, respectively.

5.2 Motion of an ion in the solenoid field.

Here a motion of an ion in the axial magnetic field of the solenoid coil is described. An analysis in this section is

limited to search for only trajectories of a guiding center in the particle motion, and then analyses with off-axis particles which is not described in the following will be given to another report.

As well known, the equations of motion in the magnetic field without any electric field are given by the next equations, using the cylindrical coordinates (r,θ,z).⁽⁹⁾

$$d^2r/dt^2 - r(d\theta/dt)^2 = (eB_z/m)r(d\theta/dt) \quad (3)$$

$$d(r^2(d\theta/dt))/dt = (e/m)r[(dz/dt)B_r - (dr/dt)B_z] \quad (4)$$

$$d^2z/dt^2 = -(eB_r/m)r(d\theta/dt) \quad (5),$$

where e and m are charge and mass of the charged particle, respectively. B_r and B_z are r and z components of the solenoid magnetic field, respectively and symbol t is time.

On the other hand, on defining φ as the magnetic flux enclosed by a radius, r and assuming that the solenoid magnetic field is cylindrically symmetry, the next equation is obtained⁽⁹⁾,

$$-(dz/dt)B_r + (dr/dt)B_z = (1/2\pi r)(d\phi/dt) \quad (6)$$

On substituting Eq.(6) for Eq.(4) and integrating the obtained equation with respect to the time, the next equation is obtained

$$r^2(d\theta/dt) + (e/m)(\phi/2\pi) = \text{constant} = C \quad (7).$$

Due to the definition of φ, φ is given by

$$\phi = 2\pi \int_0^r B_z r dr \quad (8).$$

When we select r = 0 at Eq.(8), φ = 0 is found to establish, and then the constant C of Eq.(7) should be equal to zero.

The next relations are assumed in the following,

$$B_z(r,z) = B_0 \quad (0 \leq z \leq L) \\ = 0 \quad (0 \geq z, z \geq L) \quad (9)$$

$$B_r(r,z) = 0 \quad (\text{assumed for all } z)$$

Under Eqs.(9), Eq.(8) is given by

$$\phi = \pi r^2 B_0 \quad (8)'$$

From Eqs.(7) and (8)' is obtained the next equation,

$$r^2(d\theta/dt) + (e/m)(\pi r^2 B_0/2\pi) = 0 \\ \therefore d\theta/dt = -(eB_0/2m) = \omega \quad (10)$$

Now on setting B_r=0 and (d²θ/dt²)=0 at Eq.(4), the next equation is obtained,

$$(dr/dt)[2(d\theta/dt) + (eB_z/m)] = 0 \quad (3)'$$

$$\therefore dr/dt = 0 \text{ or } d\theta/dt = -(eB_z/2m) \quad (11)$$

On substituting the former of Eq.(11), dr/dt=0 for Eq.(3), the next equation is obtained as (dθ/dt) ≠ 0.

$$(d\theta/dt) = -eB_z/m = \omega_c \quad (12)$$

Eq.(12) is the well-known equation as cyclotron frequency and is found under dr/dt=0. On the other hand, the latter of Eq.(11) is obtained setting dr/dt ≠ 0 at Eq.(4). Here an analysis under dr/dt ≠ 0 is noticed.

On substituting Eq.(10) for Eq.(3), it follows

$$d^2r/dt^2 + \omega^2 r = 0 \quad (13)$$

According to Eq.(5), the charged particles in case of $B_r = 0$ are found to move in the z direction at a constant velocity, v_z . Then the variable t can be exchanged to the coordinate z , and by using transformations, $dr/dt = v_z dr/dz \equiv v_z r'$ and $d^2r/dt^2 \equiv v_z^2 r''$ for Eq.(13), it follows

$$r'' + (\omega/v_z)^2 r = 0 \quad (14).$$

Here, on putting $\omega/v_z = \omega_0$, the next solution is obtained,

$$r = (r_0'/\omega_0) \sin \omega_0 z + r_0 \cos \omega_0 z \quad (15),$$

$$r' = r_0' \cos \omega_0 z - \omega_0 r_0 \sin \omega_0 z \quad (16),$$

where both of $(r)_{z=0} = r_0$ and $(r')_{z=0} = r_0'$ are set.

When $r_0 = 0$ is assumed, Eqs.(15) and (16) follow

$$r = (r_0'/\omega_0) \sin \omega_0 z \quad (17),$$

$$r' = r_0' \cos \omega_0 z \quad (18),$$

that is, the beam size at a given z is only dependent on r_0' . When the length of the solenoid coil, L meets the relation of $\omega_0 L = \pi/2$, we obtain $r' = 0$ and then the beam is found to enter normal to the target.

Suppose the case which the solenoid magnetic field including a time-varying term is given by

$$B_s = B_0 + \Delta B \sin \omega_k t \quad (19)$$

where ΔB and ω_k are the amplitude and frequency of the time-varying component of the solenoid field, respectively.

On substituting B_s for B_0 of Eq.(10), we obtain,

$$\omega' = \omega + \Delta \omega \sin \omega_k t \quad (20),$$

where ω is the same as in Eq.(10), and $\Delta \omega$ is equal to $(e \Delta B/2m)$.

On substituting ω' for ω in Eq.(13), we obtain

$$d^2r/dt^2 + (\omega + \Delta \omega \sin \omega_k t)^2 r = 0 \quad (21).$$

On calculating the frequency ω for proton, we obtain 144MHz on $B_0=3T$. The frequency ω_k is selected in a range of 10~100Hz and is very small compared with ω , and then the effect due to $\sin \omega_k t$ can be ignored in Eq.(21). The time which a 2.5 MeV proton for a typical neutron source takes to pass through the coil length L is very small compared with ω_k^{-1} . Therefore the time-variation of the solenoid field in the time span can be neglected. That is, Eq.(13) is similarly kept on the variation of Eq.(20), too. Moreover, on setting ω_0' equal to the equation obtained by substituting B_s for B_0 in the expression of ω_0 , it follows

$$\omega_0' = \omega_0 + \Delta \omega_0 \sin \omega_k t \quad (22)$$

where ω_0 is the same as in Eq.(15), and $\Delta \omega_0$ is equal to $(e \Delta B/2m v_z)$.

On substituting ω_0' of Eq.(22) for ω_0 of Eq.(15), it follows

$$\begin{aligned} r = & (r_0'/\omega_0) [1 - (\Delta \omega_0/\omega_0) \sin \omega_k t] \sin \omega_0 z \\ & + (r_0'/\omega_0) \cdot \Delta \omega_0 z \cdot \sin \omega_k t \cdot \cos \omega_0 z \\ & + r_0 \cdot \cos \omega_0 z \end{aligned} \quad (15)'$$

where r_0 and $\Delta \omega_0$ are assumed to be infinitesimals and their second order terms are ignored.

The target is set close to the exit of the solenoid whose length L meets the condition of $\omega_0 L = \pi/2$, and on putting r_T

for the position of the beam on the target, it follows

$$r_T = (r_0'/\omega_0) [1 - (\Delta \omega_0/\omega_0) \sin \omega_k t] \quad (23).$$

On substituting r_0' of Eq.(1) for Eq.(23), it follows

$$r_T = (r_A'/\omega_0) \quad (24),$$

where a second order term $(\Delta \omega_0/\omega_0) \times (\Delta r_A'/r_A')$ is neglected and moreover the next relations are used,

$$\omega_k = \omega_M \quad (25),$$

and

$$(\Delta r_A'/r_A') = (\Delta \omega_0/\omega_0) = (\Delta B/B) \quad (26).$$

That is, r_T is found to have no variation in the radial direction by making the time variation of the solenoid field synchronize one of the wobbling magnets as given by Eq.(25), and moreover by setting the relation between amplitude ratios given by Eq.(26).

On changing the incident angle according to Eq.(1), the beam position at the beam entrance is shifted from the intersection point O , and r_0 become to be not equal to zero, but no effect be found to appear on Eq.(24) within the first order approximation already described above.

Thus the position of the proton incident into the solenoid field is kept r_T on the target constant and is rotated by the amount given by $\omega_0 L + \Delta \omega_0 L \sin \omega_k t$ between the entrance and exit side. That is, the beam on the target is oscillated with the amplitude in azimuthal angle which is equal to $(\pi/2)(\Delta \omega_0/\omega_0)$ by the time-varying solenoid field without changing the radial position at the exit of the solenoid field. Additionally, when the proton beam energy, the coil length L and field strength B_0 are set around 2.5MeV, 22.5cm and 3.2T, respectively, then r_T , r_A' and ω_0 are found to have 2.5cm, 0.175rad. and 0.07 cm^{-1} , respectively.

6. Ion intensity distributions on the target

Each beam arrives at the location on the target shown in Fig.2. Here are described some intensity distributions which are obtained on superimposing the five beams on the target. After some cases without the time-varying solenoid field are at first described, some cases with the time-varying one are shown in the following.

Now, a charged particle intensity distribution with the standard deviation σ and the medium μ for the beam, whose center on the target is located at a coordinate point $(\mu \cos \theta, \mu \sin \theta)$ (θ : the azimuthal angle in Fig.2), is assumed to be given by the two dimensional gaussian one,

$$\begin{aligned} f(x, y, \theta) = & (1/2\pi \sigma^2) \cdot \exp[-\{(x - \mu \cos \theta)^2 \\ & + (y - \mu \sin \theta)^2\}/2\sigma^2] \end{aligned} \quad (27).$$

For example, such resultant strength distributions as shown in Figure 4 can be expected on the target. In the figure are shown only the first quadrant (one fourth) of the rectangular coordinates (X, Y, Z) defined in Fig.2.

The standard deviations and the mediums for the beam lines, A, B, C and D, are expressed by σ_2 and μ_2 , respectively. They for the beam line E are defined by σ_1 and $\mu_1 (=0)$, respectively. Also σ without any subscript for

Fig.4 Examples of the resultant strength distributions of the five beams without the time-varying field.

the beam line E means to be the same as in the four off-axis beam lines. In Fig. 4, σ is fixed at 1.0 in cm, and μ_2 values for Fig.4a), b) and c) are put 1.55, 2.33 and 3.0 in cm, respectively. θ 's for the four beams are selected at 0, $\pi/2$, π and $3\pi/2$, respectively. With increasing μ_2 , the intensity distribution is found to change from a distribution which has one top, through one which has comparatively homogenous one, and then to one with the three tops which are produced on $\mu_2 = 3.0$ cm. Now, one of the distributions that are searched for in this paper is just such a homogenous one as in case of $\mu_2 = 2.33$ mm of Fig.4.

Figure 5 shows the intensity distributions in which only σ_1 's are set for three values, 1.3, 1.33 and 1.7 cm, and σ_2 and μ_2 are fixed on the same value, 1.0 cm and 2.2 cm as in Fig.4, respectively. As far as we say on limiting on the x or y axis, the case of $\sigma_1 = 1.33$ cm is found to be better than in the other two cases. However the results have large valleys as there is no beam in the direction of 45° angle. The beam line E has three series of quadrupole magnets and a set of scatterers which scatters the beam and spreads its size, and then its beam stretch can be changed into such desired one as is selected in Fig.5. Thus widely homogenous intensity distributions which are, for example, better than $\pm 5\%$ in homogeneity over 40 mm in diameter are obtained only in the x and y direction.

Next, ion intensity distributions with the time-varying solenoid field are described in the following.

The distribution of the beam A are expressed with suffix A and likely, with suffixes B, C and D for them of the beam B, C and D, respectively.

Fig.5 Examples of the resultant strength distributions of the five beams without the time-varying field.

At first, suppose the beam A is vibrated around θ by $\pm \Delta\theta$, which is equal to $(\pi/2)(\Delta\omega/\omega_0)$. When f_A expressed on the cylindrical coordinates (r, θ) are integrated from $\theta - \Delta\theta$ over $\theta + \Delta\theta$, and divided by $2\Delta\theta$, the integrated intensity at (r, θ) is obtained and is equal to the value at (r, θ) of the intensity distribution, $F_A(r, \theta, \pi/2)$ normalized by the total vibration width $2\Delta\theta$.

On converting the rectangular coordinates (x, y) into the cylindrical coordinates (r, θ) , the intensity distribution $F_A(r, \theta, \pi/2)$ is given by the next equation.

$$F_A(r, \theta, \pi/2) = \frac{\int_{\theta - \Delta\theta}^{\theta + \Delta\theta} f_A(r \cos \theta, r \sin \theta, \pi/2) d\theta}{2\Delta\theta} \quad (28)$$

Likelihood, the equations of the beams B, C and D corresponding to Eq.(28) are obtained by substituting $\pi/3$, $\pi/2$ or 0 into $\pi/2$ and moreover f_B , f_C or f_D into f_A , in Eq.(28), respectively. f_i ($i = A, B, C$ or D) are expressed by

$$f_i(x, y, a, b, \theta) = (1/2\pi\sigma_2^2) \cdot \exp[-\{(x-a)^2 + (y-b)^2\}/2\sigma_2^2] \quad (29),$$

where f_A , f_B , f_C and f_D are obtained by setting $f_A(x, y, 0, \mu_2, \pi/2)$, $f_B(x, y, 0, -\mu_2, 3\pi/2)$, $f_C(x, y, \mu_2, 0, \pi)$, $f_D(x, y, \mu_2, 0, 0)$, respectively. Also $f_E(x, y)$ is given by,

$$f_E(x, y) = (1/2\pi\sigma_1^2) \cdot \exp[-(x^2 + y^2)/2\sigma_1^2] \quad (30).$$

In the following, examples of the sum intensity distri-

bution $F(r, \theta)$ obtained on superimposing the five beams are described.

Figure 6 shows the sum intensity distributions on the (r, θ) plane obtained for four values of $\Delta\theta$ ($=\Delta\omega_0 L$), $0^\circ, 22.5^\circ, 35^\circ$ and 45° . In Fig.6, σ_1, σ_2 and μ_2 are selected 1.0, 1.25 and 2.5cm, respectively. Fig.5 is expressed on the coordinates (X, Y) whose origin is given by a point, but the origin on the coordinates (r, θ) is expanded on the whole of the θ axis in Fig.6. As a result, the homogeneity in the θ direction is found to be better with increasing $\Delta\theta$, and then $[(F(2, 0^\circ) - F(2, 45^\circ)) / F(2, 0^\circ)]$ which is typically defined as the homogeneity at $r=2.0$ cm, have $\pm 0.34, \pm 0.16, \pm 0.072$ and 0 for four values of $\Delta\theta$, $0^\circ, 22.5^\circ, 35^\circ$ and 45° , respectively.

Fig.6 Examples of the resultant intensity distributions of the five beams with the scanning apparatus.

7. Conclusions.

The major conclusions in this paper are shown in the following.

1) A scanning system composed of a solenoid coil and wobbling magnets is found to produce various intensity distributions on a target used as the neutron source for BNCT.

2) A usefulness of the proposed scanning method is confirmed by the result that better intensity distributions than $\pm 5\%$ in the homogeneity are obtained over 4 cm in diameter in the case of the five beam lines.

(Received 13 May 1998; and in revised form 16 Sep. 1998)

Acknowledgments

I would like to thank Dr.M. Yamazaki and Dr.M. Mizota for giving us useful comment on applying for patents of this idea.

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