CONSTRUCTION OF A BNCT FACILITY USING AN 8-MeV HIGH POWER PROTON LINAC IN TOKAI

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Abstract

An accelerator-based BNCT (Boron Neutron Capture Therapy) facility is now under construction and the entire system including the patient treatment system will be installed in the Ibaraki Medical Center for Advanced Neutron Therapy (tentative name). Investigation of an 8-MeV proton linac and of a beryllium-based neutron production target for the BNCT is progressing. We are aiming at the design and construction of a "Hospital and Patient friendly" BNCT system.

INTRODUCTION

BNCT is expected to give good results for inoperable cancers. In BNCT, pharmaceuticals carry a neutron capture agent containing ^{10}B (Boron 10) selectively into tumor cells. Next thermal or epi-thermal neutrons interact with the ^{10}B and produce α and ^{7}Li-particles. Both of these particles have a very high Linear Energy Transfer (LET) and therefore lose all most all of their energy within a distance comparable to the size of a tumor cell. Thus effecting a cellular-level therapy. So far, BNCT has been provided only by nuclear reactors. The promising results shown there by BNCT give the hope that it may become an indispensable treatment modality for many types of cancers. From solely the neutron intensity point of view, nuclear reactors are excellent neutron sources. But as nuclear reactors regularly require long maintenance shut-downs and are subject to strict regulations, hospital operation is completely impractical. Thus we recognize the desirability of an accelerator-based BNCT facility well adapted for use by hospitals. The development of such a BNCT requires multi-disciplinary input and collaboration from a wide spectrum of scientific and technical specialties. To obtain the needed breath and strength, we have organized our team with contributing specialists from diverse institutes and companies. The Ibaraki Medical Center for Advanced Neutron Therapy will be on the IQBRC (Ibaraki Quantum Beam Research Center) campus, which is near the JAEA and KEK Tokai campuses. The building for the BNCT is now under renovation by the Ibaraki prefectural government. We are tentatively calling this project "I-BNCT" because of the Ibaraki prefectural sponsorship.

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BASIC PARAMETERS

Design Principle

To realize a moderate treatment time according to the recommendations of the IAEA[1)], a neutron intensity of 1×10^9 n/cm^2/s, with energy between 0.5-eV and 10-keV is required. If possible and even shorter treatment time would be preferable. But supplying this intensity of neutrons requires quite a high power proton beam. But this high power requirement makes it difficult to keep the residual radioactivity as small as possible, both for daily patient treatments and for routine machine maintenance work. And as progress in the development of medical equipment is so rapid, plans for the removal and replacement of the BNCT system should be also taken into account from the earliest design stage. Intense neutron irradiation can generate some troublesome byproducts such as tritium and other toxic and radioactive materials. Avoiding the production of these troublesome materials as much as possible is therefore important in the design.

Target Material Selection

The selection of the target material is crucially important. With low energy protons, beryllium (Be) and lithium (Li) are both possible candidates for the target material. Lithium is very attractive because it has a low energy threshold for neutron generation. Furthermore, since those neutrons have lower energy, the neutron loss during moderation process is reduced. With a Lithium target, $^{7}Li(p,n)^{7}Be$ is the major neutron generating reaction. However, some of the neutrons will hit and react with the ^{6}Li isotope which unavoidably remains in the Li target. This reaction process, $^{6}Li(n,t)^{4}He$ is often proposed for a tritium breeding process in many conceptual designs of nuclear fusion reactors and has large cross section. On the other hand, beryllium has a higher energy threshold than lithium, requiring a higher energy accelerator. But unlike lithium, the material itself is quite stable in a normal atmosphere. And it is inactive with water. Furthermore, neutron generation through the $^{9}Be(p,n)^{9}B$ reaction is ideal because ^{9}B is very short-lived radionuclide. Many other factors, such as melting temperature, thermal conductivity, and thermal diffusion-constant and so on must also be taken into consideration. After studying the relative merits and difficulties, we have selected beryllium as the target material best meeting our design goals.

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Energy of Accelerator

Once the target material is decided, what is the most suitable incident proton energy? It is obvious that protons with higher energy generate higher neutron flux. But, as the neutrons generated would also have a wide energy spectrum with a high energy tail which would have to be moderated by some appropriate materials to produce the required energy span. Conversely, lower proton beams would generate lower neutron energy spectrum and thus a thinner moderator would be required. So from the moderation efficiency point of view, lower energy protons are advantageous. The maximum energy of neutrons produced by a proton beam is lower than the energy of an incident protons by about 2 MeV. The neutron cross-section data from many kinds of materials show that most materials have very small neutron cross-section below 6-MeV. This implies that we can expect very low radioactivity from an 8-MeV proton accelerator. We have simulated the following three parameters versus incident proton energy: neutron generation efficiency, neutron moderation efficiency and residual radioactivity of several important materials such as iron, lead, aluminum and copper. The results showed that the required neutron intensity would be obtainable with an 8-MeV, 80-kW proton beam. The calculated residual radioactivity irradiated by four different proton energy (8, 17.2, 22, 35 MeV) is shown in Fig. 1. This gives a rough outline of residual radioactivity. Detailed simulation will be carried out after fixing the target, moderator, collimator and shield configuration.

The 8-MeV proton accelerator was adopted based on these simulation works. The trade-off in adopting a lower proton energy is that the beam power must become higher and effective heat removal from the target become crucial.

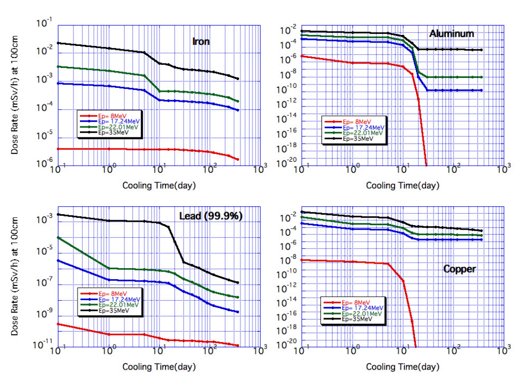

Figure 1: Calculated radio-activations after one year of continuous operation with a one microampere proton bean on target. The subsequent decay of the residual radioactivity for various materials is shown. The neutron target is beryllium. Activation of the test materials set behind the target was calculated and the radiation at 100 cm separation the 1-cm^3 test piece is plotted. In all figures, 8 MeV energy plot falls the lowest, with 17, 22 and 35 MeV results rising above.

DESIGN AND PRESENT STATUS

Accelerator

Many components can be based on those developed for J-PARC (Japan Proton Accelerator Research Complex[2)]). For example, the high current RFQ and a front part of the DTL at the J-PARC provide a good start for the accelerator design. The beam dynamics in the high current region would be quite similar to J-PARC. But intensity required by the BNCT is quite high compared with that of J-PARC. We propose realizing the higher power beam by increasing the duty cycle from the 2.5% of J-PARC up to 20% (1 ms, 200 Hz), while keeping the same peak proton-beam current of 50 mA. This technical choice then forces us to develop an improved cooling design for the accelerating structures. So while the beam dynamics for the high current beam would be kept as is, many other things will have to be changed to reduce construction cost. For example, the electrically excited Q-magnets of the DTL would be replaced with permanent magnets. Both the RFQ and 3-meter DTL are now being manufactured by Mitsubishi Heavy Industries LTD.. A bird's-eye view of the BNCT and photos of accelerating structures developed at J-PARC are shown in Fig. 2.

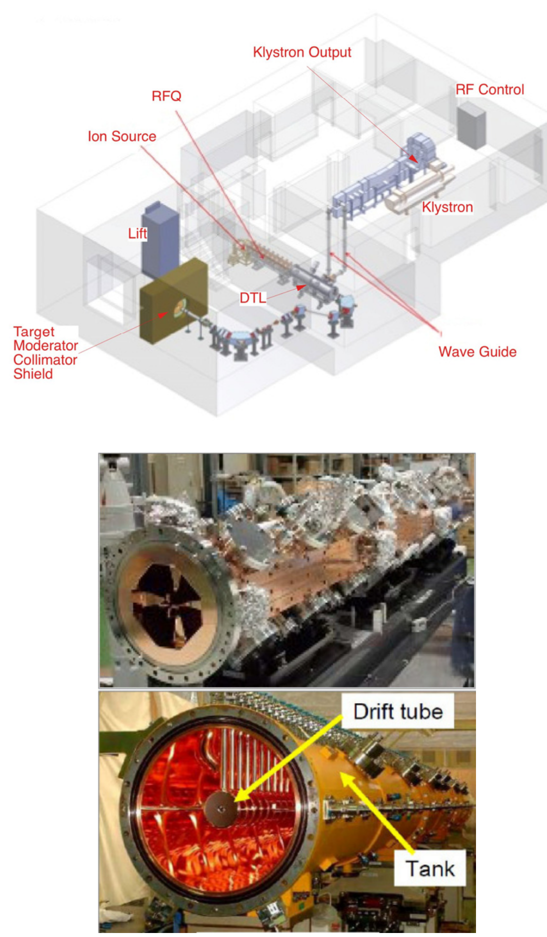

Figure 2: Bird's-eye overview of the BNCT facility (above) and photos of RFQ and DTL of J-PARC.

Target

The neutron production target is a 0.5 mm thick beryllium piece bonded to a 150 mm diameter heat sink disk. The thickness of the beryllium is chosen to be slightly thinner than the Bragg peak range of an 8-MeV proton beam. The heat load density on this target would be about 4.5 MW/m^2, which exceeds the normal surface heat exchange region capacity, and so the nucleate boiling region must be used to remove this high density heat flux[3)]. Special attention should be paid to mitigating the blistering of the target material due to hydrogen implantation as well. Blistering could be the main factor in limiting the target lifetime[4),5)]. We are now designing the target based on established technology. At the same time, we have started an R&D project studying blistering-resistant materials using a 750-kV Cockcroft-Walton proton accelerator at KEK. Many promising materials will be irradiated by a high density proton beam and their blistering characteristics will be measured.

Moderator and Expected Performance

The dose distribution inside a phantom is of interest for all kinds of radiation therapy. The goal is always to deliver the quoted dose to tumor region while keeping as low as possible the exposure to surrounding normal tissue. However, some radiation dose in the normal tissue is inevitable, and in particular, fast neutrons with energies above 10 keV, thermal neutrons with energies below 0.5 eV and all gamma-ray intensities should be kept lower than the guidelines promulgated by the IAEA. The detailed design of the moderator is now underway and will be continued to improve the dose distribution. So far we have one candidate which satisfies the IAEA guideline. An example irradiation dose both in tumor and normal tissue traversing a phantom is shown in Fig. 3. The result strongly depends on the concentration of the drug as well as its concentration ratio between tumor and normal tissue. In our simulation, a BPA drug producing a boron concentration of 30 ppm in tumor and 10 ppm in tissue was postulated.

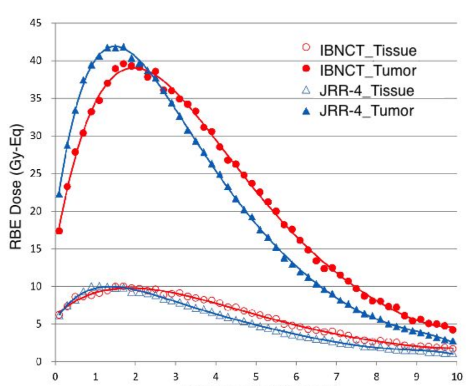

Figure 3: Simulated depth-dose curve. This work (IBNCT) and result of JRR-4 (reactor based) are shown.

Maintenance Scenario

The medical staffs working area should be kept at a sufficiently low radiation level. The materials used in the neutron moderator system including the target should be carefully selected to have reduced residual radioactivity. Nevertheless, since thermal neutrons potentially activate many materials by a neutron capture process, some amount of residual radioactivity would be unavoidable. Judging from the maintenance experience at J-PARC, 1 mSv/h at a 30 cm distance is the critical dose rate which would still allow hands on maintenance. Semi-remote maintenance mechanism will be developed for the regular proton target replacement and removal.

SUMMARY

We are now constructing an accelerator-based BNCT system. The BNCT system will be installed in the Ibaraki Medical Center for Advanced Neutron Therapy (tentative name). The incident proton energy is 8 MeV with a power of 80 kW to reduce residual radioactivity. The target material is beryllium. First beam acceleration is expected by the end of March 2013. After commissioning of the accelerator and target/moderator system, medical use application is slated to start in March 2014.

ACKNOWLEDGEMENT

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