CONCEPTUAL DESIGN OF AN RFQ ACCELERATOR-BASED NEUTRON SOURCE FOR BORON NEUTRON-CAPTURE THERAPY*

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Abstract

We present a conceptual design of a low-energy neutron generator for treatment of brain tumors by boron neutron capture therapy (BNCT). The concept is based on a 2.5-MeV proton beam from a radio-frequency quadrupole (RFQ) linac, and the neutrons are produced by the ^{7}Li(p,n)^{7}Be reaction. A liquid lithium target and modulator assembly are designed to provide a high flux of epithermal neutrons. The patient is administered a tumor-specific ^{10}B-enriched compound and is irradiated by the neutrons to create a highly localized dose from the reaction ^{10}B(n, α)^{7}Li. An RFQ accelerator-based neutron source for BNCT is compact, which makes it practical to site the facility within a hospital.

Introduction

A low-energy neutron generator was proposed[1,2] a few years ago based on a proton RFQ[3] linac. The RFQ would deliver a high-current proton beam at 2.5 MeV to a thick ^{7}Li target to produce neutrons from the well known ^{7}Li(p,n)^{7}Be reaction. When combined with a compact neutron moderator, a 10-mA proton beam current could produce a thermal neutron flux of 2×10^{11} n/cm^{2}s. Although the earlier proposal emphasized the thermal neutron flux, an RFQ-based epithermal neutron source can be designed from this same neutron generator[4-6] for treatment of brain tumors by BNCT.

In BNCT, a patient is administered a tumor-specific ^{10}B-enriched compound and is then irradiated with epithermal neutrons. If the ^{10}B attaches to or is incorporated into tumor cells with high specificity and concentration, but is in low concentration in the blood at the time of irradiation, then the ^{10}B(n, α)^{7}Li reaction products create a radiation dose that is highly localized to the tumor. Studies[4-6] confirm the potential of a low-energy proton facility to generate epithermal neutrons with an acceptable energy spectrum and intensity. Monte Carlo studies show that a 10-mA proton beam can produce a useful neutron flux of 5.0×10^8 neutrons/cm^{2}s. For a single irradiation session of 20 Gy (100 rad) to the tumor, a treatment time of 1.5 hours is necessary. To reduce the patient's irradiation time, it is desirable to increase the beam current. Beam currents of more than 40 mA have been accelerated in an RFQ operating at 100% duty factor.[7] However, as the beam current increases, the capital and operating costs of the radio-frequency power for the accelerator increase, and beam-heat removal from the liquid lithium target becomes more difficult. Ultimately, the choice of beam current will be determined by the trade-off between cost and treatment time.

Accelerator Conceptual Design

We present a conceptual design of an RFQ-based 2.5-MeV, high-current proton accelerator for BNCT. Space-charge effects in the RFQ govern the maximum permissible beam currents. Although we believe beam currents of 100 mA and higher are practical for 100% duty factor, we have chosen 30 mA for this first example. Figure 1 shows a schematic of the overall RFQ-linac BNCT treatment facility,

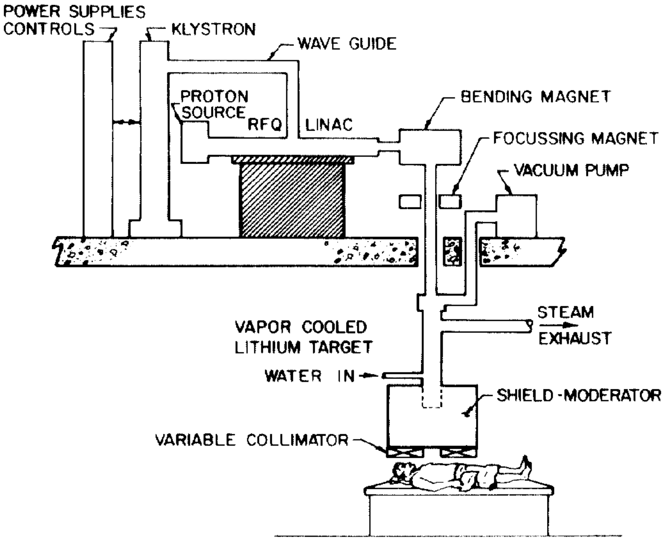

Fig. 1. Schematic of RFQ linac BNCT treatment facility.

including the accelerator system, a vapor-cooled liquid lithium target, the neutron moderator assembly, and a patient undergoing treatment. A block diagram of the accelerator system is shown in Fig. 2, consisting of an ion source, the low-energy beam transport (LEBT), an RFQ linac, a high-energy beam transport (HEBT) system, and the radio-frequency power system for the RFQ.

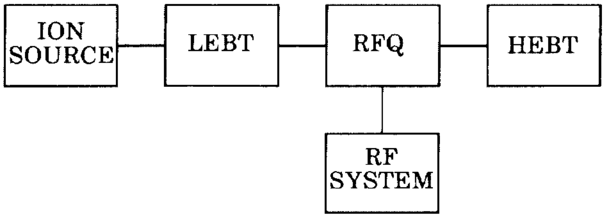

Fig. 2. Block diagram of accelerator system.

An ion source with cusped-field confinement and with single-gap extraction would provide reliable performance at 30 kV with 35-mA extracted H$^+$ beam current. The LEBT would consist of a two-lens, magnetic solenoid focusing channel in a point-to-parallel/parallel-to-point configuration. This LEBT design has sufficient flexibility to match a wide range of extracted beams into the RFQ acceptance. Based on initial design calculations, the solenoids would operate at about 0.5 T, and the LEBT length would be approximately 0.5 m.

An RFQ has been designed using the codes and procedures developed at Los Alamos with the objective of providing high transmission and high beam quality, while keeping both the electrical and physical lengths short and the power requirement low. The major engineering

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challenge for cw accelerators is the removal of heat generated by rf power dissipation on the cavity walls and the prevention of temperature changes that detune the cavity. We have produced an unoptimized design example for the RFQ, and have simulated the performance, including space charge, using the program PARMTEQ. The design and performance parameters are shown in Table I. The calculated beam profile plots for displacement x, and phase and energy relative to the synchronous particle are shown in Fig. 3. Initial and final phase-space distributions are shown in Fig. 4.

Table I. Design and Performance Parameters of the RFQ

Frequency	350 MHz
Injection energy	30 keV
Final energy	2.5 MeV
Length	3.0 m
Bore radius, r_0	0.20 – 0.27 cm
Modulation parameter, m	1.00 – 2.58
Intervane voltage	0.050 MV
Input current	33 mA
Output current	30 mA
Input emittance*	0.010 π cm·mrad
Output emittance*	0.010 π cm·mrad
Output rms energy spread	15 keV
Structure power	107 kW
Beam power	76 kW
Peak surface electric field	34 MV/m

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* The tabulated emittance values are επ, where ε is the normalized rms value without the factor of 4 that is sometimes used.

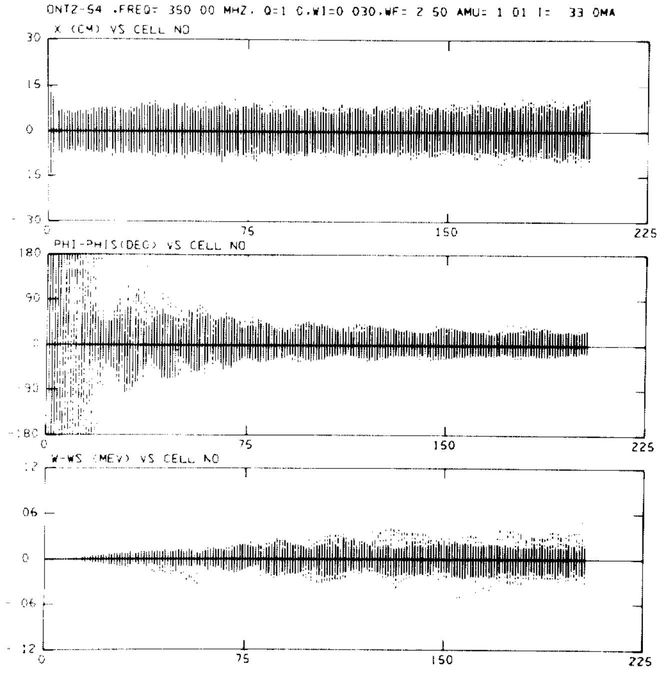

Fig. 3. Beam profile plots for RFQ simulation.

The total rf power requirement, including beam power, cavity losses, and overdrive for control, is approximately 200 kW. The CW klystron tubes operating at 350 MHz are available commercially at 1 MW of rf power. The dc power required is approximately twice the rf value and is supplied at 100 kV for the 1-MW operation. To operate at a 200 kW rf power level, the dc high voltage is reduced, which should result in exceptionally reliable performance. The klystron controls are relatively simple for cw operation where no high-voltage switching is required.

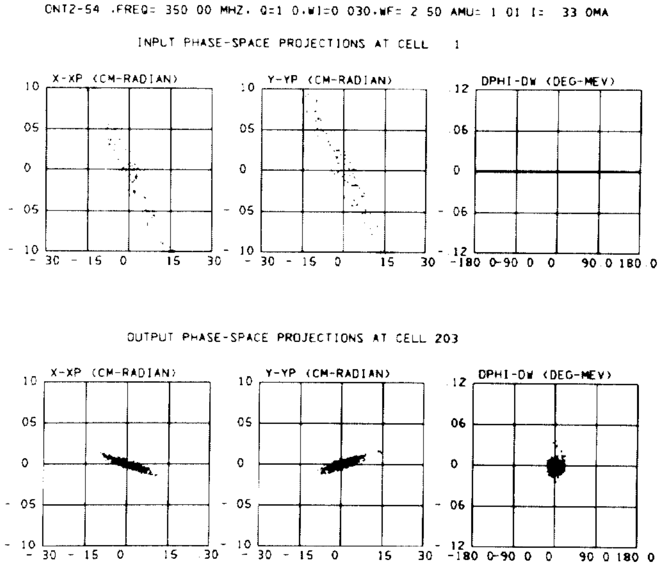

Fig. 4. Initial and final beam phase-space plots for RFQ simulation.

The HEBT design has not yet been investigated, but we believe this should be a relatively straightforward design to transport the beam from the RFQ and to distribute it uniformly on the lithium target. The control and instrumentation requirements for the accelerator should also be straightforward.

Target and Moderator Conceptual Design

A moderator assembly is shown in Fig. 5. The moderator assembly has been designed to make the gamma-ray dose as low as possible and yet transmit to the patient a large fraction of the source neutrons, degraded in energy to between 1 eV and 10 keV. The forward-directed neutrons are moderated by beryllium oxide (BeO), and control of the average energy of the neutrons emerging from the moderator assembly is achieved by adjusting the thickness of the BeO. It is anticipated that when treating deep-seated

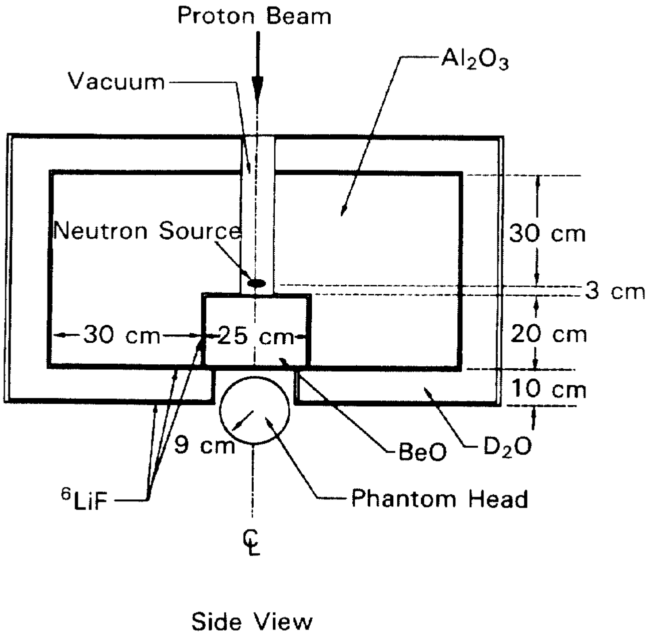

Fig. 5. The configuration of the final design of the moderator assembly.

tumors, more energetic neutrons will be required than for superficial tumors. The forward-directed neutrons are the most energetic and require the higher moderating power of BeO; whereas the neutrons born at wider angles are less energetic and require less moderation and more reflection by the alumina that they encounter.

We have evaluated the performance of the moderator assembly, which is illustrated in Fig. 5. The moderator assembly consists of a cylindrical moderator of BeO, which is 25 cm in diameter and 20 cm in height, surrounded by a 30-cm-thick alumina reflector. A loading of 0.05 g/cm^2 of ^{6}Li is placed at the interface between the moderator and reflector regions, to reduce the gamma-ray dose arising from the ^{27}Al(n, γ)^{28}Al reaction. Also, a loading of 0.01 g/cm^2 of ^{6}Li is placed at the window of the irradiation port to reduce the thermal neutron contamination. In addition, a 10-cm-thick layer of D_2O, which is in turn surrounded by an outer skin of ^{6}LiF, functions as a neutron shield to reduce the patient's whole-body dose. The escaping neutrons are thermalized by the D_2O and are then captured by ^{6}Li. Conventional neutron shielding, such as borated polyethylene, is not appropriate for our moderator assembly because both hydrogen and boron produce secondary gamma rays by capturing thermal neutrons.

The geometrical model of our moderator assembly contains a neutron source that is uniformly distributed over a 10-cm^2 area on the top surface of the inner (BeO) cylinder on the cylinder's centerline. The neutron source has the distribution in energy and angle that is produced by a beam of 2.5-MeV protons traveling parallel to the moderator assembly central axis. The model also contains a 10-cm radius spherical phantom head ($C_5H_{40}O_{18}N$) located on the moderator assembly central axis with its center 15 cm from the assembly base. Our analysis models two distinct processes: (1) neutron generation in the ^{7}Li target, and (2) neutron and gamma-ray transport in the moderator assembly and head phantom.

Neutron generation in the ^{7}Li target was calculated by simulating the production of neutrons, as protons slow down in the target, using the doubly differential cross-section for the ^{7}Li(p, n)^{7}Be reaction[8] and the stopping power for protons in lithium.[9] Neutron transport in the moderator assembly was calculated using the Monte Carlo code MORSE.[10] For the moderator assembly in Fig. 5 with a 30-mA proton beam producing 2.1×10^{13} n/s, the useful neutron flux (i.e., the flux with neutron energy >1 eV) evaluated at the irradiation point is 1.5×10^9 n/cm^2-s. The corresponding absorbed dose rates for neutrons and gamma rays are 5.7 and 1.9 cGy/min, respectively. The ratio of the neutron absorbed dose rate to the useful neutron flux is 6.5×10^{-11} cGy/n-cm^{-2}, which is slightly higher than, but comparable to, the value of the ratio that has been estimated for a proposed reactor beam.[11]

Generally speaking, for the neutrons produced by our conceptual neutron irradiation facility, the ratio of the entrance absorbed dose to the peak absorbed dose for normal tissue is larger than for an ideal 2-keV reactor neutron beam. The maximum absorbed dose to a tumor[6] is 4.88×10^{-14} cGy/source neutron for a ^{10}B concentration of 30 µg/g tumor. Therefore, for a 30-mA beam and 2.1×10^{13} n/s, the maximum absorbed dose rate is 1.02 cGy/s. For a single-session irradiation of 20 Gy to the tumor, the treatment time is about 33 min. This treatment time is quite reasonable, and could be reduced to about 11 min. with a 100 mA RFQ.

Acknowledgments

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