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TARGET STUDIES FOR ACCELERATOR-BASED BORON NEUTRON CAPTURE THERAPY*

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ABSTRACT

Two new concepts, NIFTI and DISCOS, are described. These concepts enable the efficient production of epithermal neutrons for BNCT (Boron Neutron Capture Therapy) medical treatment, utilizing a low current, low energy proton beam impacting on a lithium target. The NIFTI concept uses an iron layer that strongly impedes the transmission of neutrons with energies above 24 KeV. Lower energy neutrons readily pass through this iron "filter", which has a deep "window" in its scattering cross section at 24 KeV. The DISCOS concept uses a rapidly rotating, high g disc to create a series of thin (~ 1 micron thickness) liquid lithium targets in the form of continuous films through which the proton beam passes. The average energy lost by a proton as it passes through a single target is small, approximately 10 KeV. Between the targets, the proton beam is re-accelerated by an applied DC electric field. The DISCOS approach enables the accelerator - target facility to operate with a beam energy only slightly above the threshold value for neutron production - resulting in an output beam of low-energy epithermal neutrons - while achieving a high yield of neutrons per milliamp of proton beam current.

EXECUTIVE SUMMARY

Previous studies of accelerator/target systems designed to generate neutrons for BNCT (Boron Neutron Capture Therapy) medical treatment generally have required high proton beam currents, on the order of several tens of milliamps, with energies that are well above the threshold for neutron production. Accelerators for producing beam currents at this level are technically challenging, and costly as well. In addition, the target generated neutron energy spectrum typically has a substantial fast neutron component that would cause objectionable radiation dose in normal, non-cancerous tissue. The gamma dose to normal tissue is also significant. Finally, cooling of the accelerator targets at the required power levels is difficult.

In these previous designs, the high energy neutrons generated by the target/proton interactions are degraded to the treatment regime, i.e., on the order of 10 keV in energy, by scattering collisions with a suitable moderator (e.g., BeO, Al_2O_3, etc.) With such materials, to achieve the requisite energy degradation needed for a useful energy spectrum, the target must be located at some distance from the patient treatment zone. Consequently, for such systems the neutron utilization efficiency, that is, the ratio of the rate at which useful neutrons are introduced into the patient treatment zone to the rate at which neutrons are generated by proton/target interactions is typically in the range of 0.1 to 0.5 percent. That is, only 1/1000 th to 1/200 th of the neutrons in the target actually are available for use in the patient treatment zone. However, such efficiencies are still orders of magnitude greater than those achieved by medical reactor systems. Because of the inherently much greater distance between the neutron generating reactor core and the patient treatment zone - due to the inherent dimensional constraints imposed by criticality and the shielding requirements - the neutron utilization efficiency for medical reactors is on the order of 10^{-6}. Thus for medical reactors, only about one millionth of the generated neutrons actually are available for use in the patient treatment zone.

Two new concepts are proposed that greatly increase the neutron effectiveness and utilization efficiency of accelerator-target sources for BNCT applications. The first concept, termed NIFTI (Neutron Intensification by Filtered Transmission through Iron), utilizes materials that tailor the neutron energy spectrum more effectively than conventional elastic scattering moderators. These materials enable the patient treatment zone to be located much closer to the target source, enabling a substantial increase in neutron utilization efficiency. Moreover, the energy distribution of the neutrons that reach the patient treatment region can be shaped and optimized for maximum effectiveness, typically with an average energy on the range of 10 to 30 keV, depending on design.

The second concept, DISCOS, employs a rapidly rotating disc to form a series of ultra thin targets (in the order of 1 micron in thickness) for the

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proton beam. The proton energy loss in traversing one target is small, on the order of 10 to 20 keV. The proton beam is successively re-accelerated between the series of thin targets, and operates just above the threshold value for neutron production. The average energy of the neutrons thus produced is then much less than those produced by a higher energy beam impacting a thick fixed target.

INTRODUCTION AND BACKGROUND

Boron Neutron Capture Therapy (BNCT) is a promising approach for the treatment of inoperable brain tumors and other cancers (Farr (1954), Slatkin (1991), Harling (1989)). BNCT employs a boron containing compound that is preferentially taken up by cancer cells in the brain. When the ^{10}B in the compound absorbs a neutron, an energetic (MeV) alpha particle is released, killing the cell where the absorption takes place.

Energetic epithermal neutrons, as proposed by Fairchild (1965), enable penetration to the site of the tumor. Achieving a suitable neutron energy spectrum is very important for effective treatment. If the neutron energy spectrum is too low, their penetration depth into tissue is too small to reach the site of the tumor; if too energetic, the radiation dose to normal tissue is excessive.

BNCT treatment effectiveness is being experimentally investigated using nuclear reactors as the source of neutrons. In the U.S., several patients have been recently treated at Brookhaven Medical Research Reactor (BMRR), located at Brookhaven National Laboratory. Leakage neutrons from the core are moderated and collimated to produce a suitable beam at the external treatment port.

Reactors have very low neutron utilization efficiencies. Typically, only about 10^{-6} of the neutrons that are released in the core are actually available at the treatment port. This is a result of the inherent dimensional constraints imposed by criticality, and the relatively long distances required to slow-down high energy neutrons using conventional moderator. Gamma shielding requirements are also a contributing factor. As a result, in the BMRR, for example, the treatment port is located at a distance of 177 centimeters from the center of the core. In the MURR (Missouri University Research Reactor) BNCT design, the treatment port is 310 centimeters from the center of the core.

As a result of this very low neutron utilization efficiency, a reactor based neutron source for BNCT requires high operating power, on the order of several megawatts, and is a large, very expensive, one of a kind facility with a limited capability to treat large numbers of patients.

In contrast, accelerator based neutron sources for BNCT appear to have very attractive features, as compared to reactor based neutron sources: much lower facility cost, greatly reduced residual radioactivity, much lower operating power, greatly reduced safety concerns, and a better neutron energy spectrum for treatment.

Compared to reactor based BNCT facilities, accelerator based facilities could be located at a much larger number of sites, enabling many more patients to be treated.

Various concepts for accelerator based BNCT systems have been proposed, in which a particle beam interacts with a target to generate neutrons. Depending in the particular concept, the nuclear reaction involved can be a (p, n) reaction, a H^3 (d, n) He^4 reaction, and so forth.

A particularly promising approach is the proton beam - lithium target concept, in which a low energy proton beam (E ~ 2 MeV) strikes a lithium target, generating neutrons by the (p, n) reaction. Its attractive features include:

- Relatively high neutron yield per proton (~ 10^{-4})
- Low maximum energy of generated neutrons
- Simple, low energy proton accelerator
- Simple, readily cooled target
- Minimal shielding and residual radioactivity

A number of design studies of the proton beam - lithium target concept have been carried out. These previous studies, while they show that the concept is feasible, end up requiring the proton beam current to be in the range of 50-100 milliamps in order to achieve adequate neutron flux at the treatment port.

In the remainder of this paper, we examine new and more efficient approaches for degrading the energy and tailoring the spectral distribution of neutrons generated by a proton beam impacting a lithium target. These new approaches enable the design of accelerator based BNCT facilities that can deliver useful neutron irradiation fluxes with considerably smaller proton beam current requirements.

THE NIFTI CONCEPT

Previous design studies of accelerator driven neutron sources for BNCT therapy have achieved only relatively low neutron utilization efficiencies. Here, neutron utilization efficiency is defined as

$$\eta_N = \frac{(J_n)_T A_T}{S_N} \tag{1}$$

where

A_T = area of treatment port, cm^2

$(J_n)_T$ = neutron current at treatment port, n/cm^2 sec.

S_N = neutron generation rate at accelerator target, neutrons/sec.

Typically, the neutron utilization efficiency for accelerator targets in these studies has been in the range of $1x10^{-3}$ to $5x10^{-3}$, depending on design. For a practical treatment facility, $(J_n)_T$ should be on the order of 10^9 n/cm^2 sec., and A_T on the order of 10^2 cm^2. For a neutron utilization efficiency of ~$1x10^{-3}$, this requires a proton beam current of ~ 100 milliamps, an impractically large value. The neutron utilization efficiency for a reactor based neutron source is much smaller, on the order of 10^{-6} for the BMRR. This is a result of the necessarily much greater distance of the treatment port from the reactor core, as compared to an accelerator driven target.

It is very desirable to develop neutron conditioning/transport designs that can achieve much greater neutron utilization efficiencies for BNCT therapy. With a neutron utilization efficiency of 10^{-1}, for example, the proton current for a useful accelerator - target source needs only be about 1 milliamp. A new neutron conditioning/transport concept termed NIFTI (Neutron Intensification by Filtered Transmission through Iron) is proposed. NIFTI uses a thick iron containing "layer" to filter out unwanted high energy neutrons while letting neutrons of acceptable energy for treatment pass though almost unimpeded. Iron has a large "window" in its scattering cross section at 24 kev (Figure 1). The minimum scattering cross section is less than 1 barn; at a few kev above the "window", the cross section increases to ~ 100 barns.

Two neutron transport geometrics are possible for NIFTI:

1. open cavity (OC) geometry
2. closed solid (CS) geometry.

In the open cavity geometry the neutron source, plus its iron filter, are located in an open cavity. Neutrons transmitted through the iron filter are scattered from the cavity walls. They finally either escape through the treatment port, are absorbed, or diffuse outwards through the cavity walls.

The treatment port may be an open window, or it may incorporate a gamma shield (optional) to reduce unwanted radiation dose to patients.

In the closed solid geometry the neutron source, together with the iron filter, are enclosed by a close fitting reflector. Neutrons transmitted through the iron filter at the treatment port directly interact with the patient, while a portion of the neutrons that interact with the surrounding reflector are scattered back into the treatment port.

The closed solid geometry permits the neutron source to be located at the minimum possible distance from the patient, which acts to increase neutron utilization efficiency. However, the neutrons leaving the source that do not travel in the direction of the treatment port tend to be lost by diffusion, though a portion is scattered back towards the port. The open cavity geometry collects and returns scattered neutrons back to the treatment port. This acts to increase neutron utilization efficiency. However, since the source is located further away from the patient than is the case for the closed solid geometry, the increased distance tends to decrease neutron utilization efficiency.

Both types of neutron transport geometries require detailed MCNP neutronic analyses in order to obtain precise results. Results for closed solid geometries tend to be strongly affected by specific design parameters so that it is difficult to obtain good generalized rules. With open cavity geometries, some useful generalized results can be obtained that can help in the optimization process.

Consider an idealized open cavity geometry. It is assumed that the cavity is a "neutron hohlraum", with the neutron flux everywhere inside the cavity having the same value. This assumption is not strictly correct because of losses through the treatment port and the scattering effects due to the iron filter and fluoride layers that surround the neutron source, but it is reasonably accurate when the scattering from the cavity wall predominates - that is, when

$$\pi D_C L_C >> D_T^2 \ and \ \pi D_S^2 \qquad (2)$$

where

D_C = diameter of cavity wall, cm
D_S = diameter of source w/iron filter, cm
D_T = diameter of treatment port, cm
L_C = length of cavity, cm ($\approx D_C$)

It is also assumed that losses due to neutron absorption are small compared to losses due to diffusion through the cavity walls, and that the source neutrons are transported through the fluoride and iron filters with negligible absorption losses. Both of these assumptions are based on results of neutronic analyses.

The neutron leakage through the cavity wall can be approximated from diffusion theory, with

$$J_{CW} \cong D_{CW} \nabla \phi_C = \frac{1}{3\left(\Sigma_S\right)_{CW}} \left(\frac{\phi_C}{\Delta X_{CW}} \right) \qquad (3)$$

where

D_{CW} = diffusion coefficient in wall, cm
J_{CW} = neutron diffusion current through the cavity wall, n/cm^2 sec
ΔX_{CW} = cavity wall thickness, cm
ϕ_C = neutron flux inside cavity, n/cm^2 sec
Σ_S = macroscopic total cross section of cavity wall, cm^{-1}

$[(\bar{\Sigma}_S)_{CW} = N_{CW} (\bar{\sigma}_S)_{CW}]$

For the BNCT application, it is desirable to have a relatively low rate of neutron energy degradation in the cavity wall. To accomplish this, the average energy decrement for an elastic scattering event should be as low as possible. The average logarithmic energy decrement per scattering event in the wall, ξ_{CW}, is given by

$$\xi_{CW} = \frac{2}{3 A_{CW}} \qquad (4)$$

where

A_{CW} = atomic mass of the cavity wall material

The rate of energy degradation per cm^2 of cavity wall is approximated by

$$\left(L_R \right)_{CW} \approx \frac{\phi_C}{2} \Delta X_{CW} \xi_{CW} \left(\Sigma_S \right)_{CW} \left(\frac{1}{\Delta U_{CW}} \right) \qquad (5)$$

where

L_R = energy degradation rate, n/cm^2 sec
ξ_{CW} = average logarithmic energy decrement
$(\Delta U)_{CW}$ = acceptable lethargy decrement for neutrons

Assuming that a factor of e (= 2.72) degradation in neutron energy is acceptable [$(\Delta U)_{CW} = 1$], and that the energy degradation rate is the same order as the diffusion loss rate [$(LR)_{CW} = J_{CW}$], equations (3) and (5) can be combined

$$\frac{J_{CW}}{\left(L_R \right)_{CW}} = \frac{\phi_C}{\left(\Delta X \right)_{CW}} \left[\frac{1}{3 \left(\Sigma_S \right)_{CW}} \right] \frac{2}{\phi_C \Delta X_{CW} \xi_{CW} \left(\Sigma_S \right)_{CW}} = 1 \qquad (6)$$

Rearranging,

$$\left(\Delta X_{CW} \right) = \left(\frac{2}{3 \xi_{CW}} \right)^{1/2} \frac{1}{\left(\bar{\Sigma}_S \right)_{CW}} = \left(A_{CW} \right)^{1/2} \frac{1}{\left(\bar{\Sigma}_S \right)_{CW}} \qquad (7)$$

where

Combining equations (3) and (7)

$$J_{CW} \approx \frac{\phi_C}{3} \frac{1}{\left(A_{CW} \right)^{1/2}} \ n/cm^2 \ \text{sec} \qquad (8)$$

For an open treatment port (no gamma shield) the neutron current through the port is given by

$$J_T \approx \frac{\phi_C}{4} \ n/cm^2 \ \text{sec} \qquad (9)$$

Combining equations (8) and (9)

$$\left(\frac{J_T}{J_{CW}}\right) \approx \frac{\Phi_C}{4}\frac{3(A_{CW})^{1/2}}{\Phi_C} \approx \frac{3}{4}(A_{CW})^{1/2} \quad (10)$$

For heavy scatterers, such as lead,

$$\left(\frac{J_T}{J_{CW}}\right)_{Pb} \approx \frac{3}{4}(207)^{1/2} \approx \frac{3}{4}(14.4) \approx 10.8$$

The neutron diffusion current though the cavity wall is thus approximately 10^{-1} of the current through the treatment port.

However, the corresponding value for $(\Delta X)_{CW}$ as given by equation (7) is approximately

$$[(\Delta X)_{CW}]_P \approx \frac{(A_{CW})^{1/2}_{Pb}}{[(\Sigma_S)_{CW}]_{Pb}} \approx \frac{(14.4)}{N_{Pb}(\sigma_S)_{Pb}} \approx \frac{14.4}{3x10^{22}x11x10^{-24}} \approx 43.6\,cm$$

This thickness appears too great to be practical, since the unfavorable geometry of such a thick wall would substantially increase neutron diffusion losses.

The large value of 44 cm for lead is a consequence of the low atomic concentration ($N_{Pb} \sim 3x10^{22}$ atoms per cm^3) and modest scattering cross section ($\sigma_S \approx 11$ barns). Other materials are possible, with substantially higher cross sections and atomic cross sections.

Candidate materials include vanadium, titanium and nickel, either singly or in combination to eliminate "windows" in the scattering spectrum. Other materials that might be used in combination to eliminate windows include chromium and manganese.

These materials are characterized by high atomic densities (~ 10^{23} atoms/cm^3) and high average cross sections - on the order of tens of barns - in the multi kev energy range. Taking $N_{SW} \sim 10^{23}$ atoms/cm^3 and $\bar{\sigma}_S \sim 30$ barns, the corresponding value of $(\Delta X)_{CW}$ becomes

$$(\Delta X)_{CW} = \frac{(A_{CW})^{1/2}}{10^{23}x30x10^{-24}} = \frac{(50)^{1/2}}{3} = 2.4\ cm$$

While the above elements are excellent scatterers, with the consequent advantage that the cavity walls can be thin, they also have relatively high values of ξ (ξ for Ni, etc., is about 1/4 that for lead), making the ratio of

$$J_T/J_{CW} \sim 5 \text{ to } 6$$

as compared to ~ 11 for lead.

The situation can be improved somewhat by (singly or in combination)

1) operating with a higher value for $(\Delta U)_{CW}$, and/or
2) using a mixture of lead and some other scatterer (eg, Vanadium) for the cavity wall.

Since J_T/J_{CW} scales as $[(\Delta U)_{CS}]^{1/4}$, accepting a factor of e^2 in energy degradation (factor of 7.4) rather than 3 (factor of 2.72) increases J_T/J_{CW} by a factor of 1.4, so that J_T/J_{CW} for the vanadium, etc. type of cavity reflectors would then be in the range of 7 to 8.

Increasing the total macroscopic cross section for the cavity wall from the value of 0.33 cm^{-1} for pure lead to the value of 0.66 cm for a mixture of Pb and vanadium type of scatterer would reduce ΔX_{CW} from 44 cm down to 22 cm. In addition, ξ_{CW} would be reduced by a factor of ~ 2, as compared to a pure vanadium scatterer. These two effects would increase J_T/J_{CW} by a factor of 1.4. It thus appears possible to tailor the composition of the cavity reflector and the amount of energy degradation so as to have an acceptable wall thickness on the order of ~ 20 cm with a value of J_T/J_{CW} of about 10. Based on this value, the value of neutron utilization efficiency can be expressed for the idealized geometry as

$$\eta_N = \frac{J_T\left(\frac{\pi D_T^2}{4}\right)}{J_{CW}\left[\pi D_{CW} L_{CW} + \frac{\pi}{2}D_{CW}^2 - \frac{\pi}{4}D_T^2\right] + J_T\left(\frac{\pi D_T^2}{4}\right)} \quad (11)$$

Rearranging

$$\eta_N = \frac{J_T/J_{CW}}{\left[4\frac{D_{CW}L_{CW}}{D_T^2} + 2\frac{D_{CW}^2}{D_T^2} - 1\right] + J_T/J_{CW}} \quad (12)$$

Assuming that $D_T = 11$ cm (A ~ 100 cm^2), the cavity length to diameter ratio equals 1 ($D_{CW} = L_{CW}$), and the relative leakage ratio, J_T/J_{CW}, = 10. The outer diameter, D_S, of the neutron source (i.e., the OD of the iron filter) is assumed to be 15 centimeters. It is also assumed that the lower limits for D_{CW} is determined by the condition that

$$\left(D_{CW}^2\right)_{Lower\ Limit} = 2\,D_S^2 \quad (13)$$

This corresponds to having the minimum area of open cavity around the source neutron equal to the cross sectional area of the source. On the basis of these idealized analyses the neutron utilization for the open cavity geometry are projected to be on the order of 10 to 20%.

As noted earlier, neutron utilization efficiencies for closed solid NIFTI geometries are more difficult to estimate. In general terms, for closed solid geometries

$$\eta_N = K_{CS}\frac{A_T}{4\pi\left(\frac{D_S}{2}\right)^2} = K_{CS}\frac{A_T}{\pi(D_S)^2} \quad (14)$$

The factor K_{CS} relates to how effectively the neutrons that originally travel outwards from the source in directions away from the treatment point are scattered back to the port. The value of $K_{CS} = 1$ corresponds to a pure geometric neutron utilization. That is, η_N is just the ratio of port area to the spherical surface area for the radius $D_S / 2$. For a treatment port area of 100 cm^2, and D_S=15 cm, η_N equals 14%. With a modest amount of scattering into the treatment port, i.e., $K_{CS} \approx 2$, the neutron utilization efficiency for the closed solid version of NIFTI-1 will be comparable to that for the open cavity version.

Optimization of NIFTI will involve maximizing the neutron utilization efficiency, as discussed previously. However, other factors are also involved, including:

- neutron generation efficiency
- target simplicity, reliability, and maintainability
- directionality and energy spectrum of neutrons leaving the treatment port
- gamma dose during treatment
- residual activation of the NIFTI assembly

The neutron generation efficiency is defined by

$$\eta_G = \text{\# of neutrons generated per beam proton.}$$

η_G depends on the target design. It generally will be in the range of ~ 10^{-5} to 10^{-4} neutrons per proton.

The overall beam utilization efficiency is defined as

$$\eta_B = \text{\# of neutrons leaving the treatment port per beam proton.}$$

In terms of the neutron utilization and generation efficiencies, η_B is given by

$$\eta_B = \eta_N \, \eta_G \qquad (15)$$

η_B is thus a direct measure of the proton current required to produce the neutron current desired for treatment.

Figure 2 shows the proton beam current required, as a function of neutron generation and utilization efficiency, based on a treatment port area of 100 cm^2 and a neutron current of 10^9 n/cm^2, seen at the port. This would enable treatment times on the order of a half hour. Neutron utilization efficiency can be as low as 5% with the proton beam current below the goal of 3 milliamps.

THE DISCOS CONCEPT

A new concept is proposed for accelerator targets, termed DISCOS (Discs Incorporating Sector Configured Orbiting Sources). DISCOS appears very promising for generating neutrons for BNCT applications. DISCOS also appears promising for spallation target applications. In this paper, we examine the DISCOS concept as applied to the systems in which a proton beam impacts a lithium target to generate neutrons by the (p, n) reaction. However, the DISCOS concept could also be applied in other accelerator applications employing different particles and different targets. DISCOS creates one or more ultra thin (i.e., on the order of a few microns in thickness) lithium targets that would be impacted by the proton beam. The targets would be thin enough that the proton beam loses only a small portion of its energy - at most, a few tens of keV - in its passage through an individual lithium target.

After impacting a target, the protons in the beam would be re-accelerated to bring their energy back up to the initial value. This could be done by recirculating the beam and directing the beam back through a particle accelerator that would make up the energy lost in each repetitive pass through the lithium target. Alternatively, a multiple set of thin lithium targets can be used, within a DC electric field. The energy loss experienced by the protons in passing through a given target would then be compensated for by the energy gained in the DC field as the protons traveled to the next lithium target.

The DISCOS concept enables the efficient generation of low energy neutrons from lithium targets. The proton beam energy can be held just above the threshold value for neutron production, so that the output neutrons are born with low energies. If a single fixed target were used, however, the resultant neutron yield - i.e., neutrons generated per beam proton - would be very low, and the energy efficiency - neutrons per MeV of proton input energy - very small. By re-accelerating the protons each time they pass through a thin lithium target, both the energy yield and energy efficiency can be increased by a large factor - on the order of 10 to 100 times, depending on design - while still maintaining the output of low energy neutrons. To achieve comparable neutron yields per proton and energy efficiency with a single fixed target, the initial energy of the proton beam would have to be far above the threshold value for neutron production, with the result that the output neutrons would have much greater average energy and a much higher maximum energy.

Figure 3 shows the basic DISCOS target concept. The relatively thick support structure supports an ultra-thin (e.g., as thin as one micron, or even less) foil which intercepts the beam. The target disc is segmented into sectors so as to eliminate circumferential stresses. This enables much faster rotation, and more reliable, longer life operation. The same principle is used in the radial fiber super-fly-wheel that have been developed for energy storage applications. The particle beam intercepts only the foil. The foil is cooled by radiation and conduction (dry option) or is directly covered by a thin liquid film that flows radially outwards on the foil (wet option). The wet option can utilize a liquid, e.g., lithium, that also serves as the target. If a lithium target is used, the DISCOS approach requires a backing foil to hold the lithium film. The foil produces parasitic losses of the proton beam, increasing the proton current needed to achieve the given neutron production rate.

The foil parasitic losses can be minimized by using a foil that is made of a low Z material, and having it as thin as possible. Beryllium foil appears to be the best choice, since it has low Z (Z = 4), appears fabricable as a thin metallic foil, and generates some neutrons when impacted by a proton beam (though not as much as a lithium film of equivalent stopping power). However, the presence of the Be foils still results in a lower neutron production rate as compared to having no foils at all.

Figure 4 shows an illustrative arrangement of target foils for the re-acceleration of the proton beam in DISCOS. The proton beam first impacts a target foil at ground potential producing neutrons and losing energy as it does. It then loses further energy due to the electric field between the ground foil and the first interior target foil, which is maintained at a positive potential (e.g., +200 kv) with respect to ground.

The proton beam then passes through the sequence of target foils, and is re-accelerated by the electric fields between the sequential series of foils. In the example shown, the average energy lost by the beam is 50 keV each time it passes through a foil. The foil may either be dry (i.e., Be), or wet (i.e., Be with a lithium film). This energy loss parameter can be adjusted over a wide range, depending on design considerations. On the one hand, a small energy loss in a foil would allow DISCOS to operate slightly above the neutron production threshold, generating a directed neutron beam in which the maximum energy of the neutrons was low. On the other hand, this would require a large number of foils, since the average energy loss per foil probably would have to be in the range of 5 to 10 keV. More detailed study is required to determine the optimum number of foils.

It is important to note that the energy lost by the proton beam as it penetrates the first ground foil and is decelerated by the first target foil, which is at +200 kv, is returned during the re-acceleration process, since the last target foil in the sequence is at -200 kv. In effect, the target arrangement enables the beam to operate at a quasi-constant energy (with an integrated total energy input of $2\Delta V_1$ (where ΔV_1 is the potential of the first target foil above ground).

ΔV_1 will probably be in the range of 200 to 300 kv, so that the total energy used in the re-acceleration process will be 400 to 600 keV. [An additional energy input of ~500 keV could be imparted using a sufficiently thick first ground foil, if the higher energy neutron spectrum generated by this portion of the target is acceptable. This would increase the total energy loss per transit of the target to ~1000 keV.

NIFTI/DISCOS PRELIMINARY DESIGN

Figure 5 shows an illustrative preliminary design for the NIFTI/DISCOS concept using the closed solid geometry option. The proton beam is assumed to come into the target region parallel to the treatment port, rather than normal to it. This is done to take advantage of the softer neutron spectrum at large angles relative to the direction of the proton beam. Table 1 summarizes the input design parameters for the NIFTI/DISCOS preliminary designs, while Table 2 summarizes the output performance parameters. Table 3 gives the neutron energy distribution, calculated using a 3D Monte Carlo neutronics code (MCNP).

Two cases are analyzed for NIFTI/DISCOS, the first with a neutron down-shifter (letter "y") and the second without a down-shifter (letter "n"). The down-shifter is a 1 centimeter thick layer of water just behind the iron filter (i.e., between the filter and the DISCOS target. A proton beam energy of 1.889 to 1.904 MeV is assumed, with the beam losing 5 keV as it goes through 1 sheet of the DISCOS target. The resultant neutron source energy and angular distribution caused by the proton impacts on lithium are taken from calculations by Thieberger (1995).

The neutron utilization efficiency for the designs is very high, in the range of 12% to 18%. That is, of the source neutrons generated in the target, 12 to 18% make their way to the treatment port and exit from it. Of the total number of neutrons that escape through the front face of NIFTI assembly, approximately 70 percent escape through the treatment beam port. This fraction could be substantially increased by using thicker neutron absorber on the portion of the front face surrounding the treatment port.

The average output neutron energy without a down-shifter is 18.4 keV, which appears acceptable. For treatment where less penetration is necessary, it may be desirable to use a down-shifter, which would reduce average neutron energy to 11.6 keV. This could be done simply by filling the 1 cm thick down-shifter cavity with water when desired. Thus, the design is very flexible and would have a readily adjustable capability to deliver a range of neutron energies.

Two values are shown for the proton beam current. The high value corresponds to using just one sheet on the DISCOS assembly; the low value corresponds to using 80 sheets, with 5 keV re-acceleration between sheets, resulting in a very low proton current requirement of ~ 2 to 3 milliamps. Determination of the optimum number of sheets will require more detailed study. Approximately 100 treatment neutrons exit from the beam port per exiting gamma photon.

SUMMARY AND CONCLUSIONS

The NIFTI and DISCOS concepts appear to result in significant increases in the neutronic efficiency of accelerator targets for BNCT treatment. On the order of 10% of the neutrons generation by (p, n) reactions in a series of thin film lithium targets are available for use at the patient treatment port, with average energy in the range of 10 to 20 KeV, depending on design. The increased neutronic efficiency substantially reduces the required proton accelerator current, e.g., down to a few milliamps.

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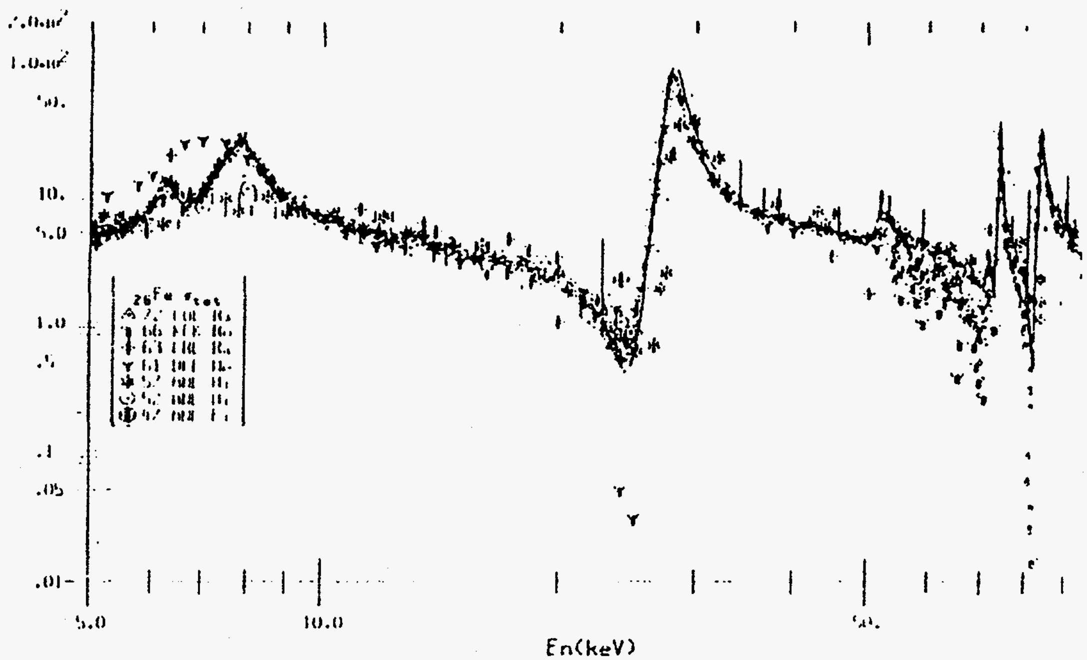

FIGURE 1
NEUTRON SCATTERING CROSS SECTION FOR IRON

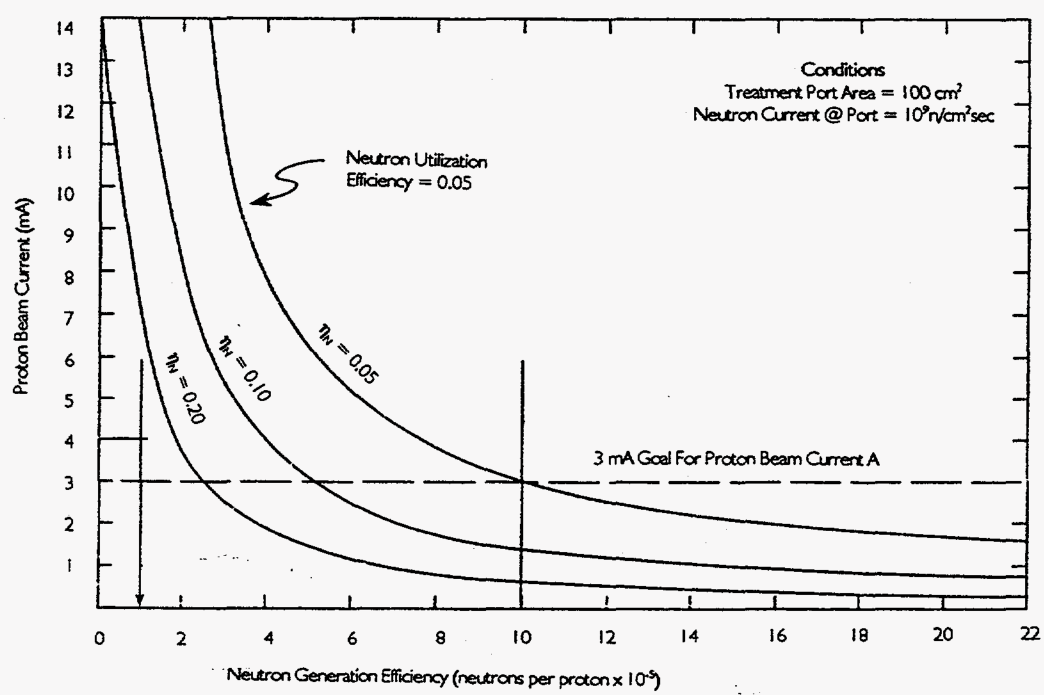

FIGURE 2
PROTON BEAM CURRENT REQUIRED AS A FUNCTION
OF NEUTRON GENERATION AND NEUTRON UTILIZATION EFFICIENCY

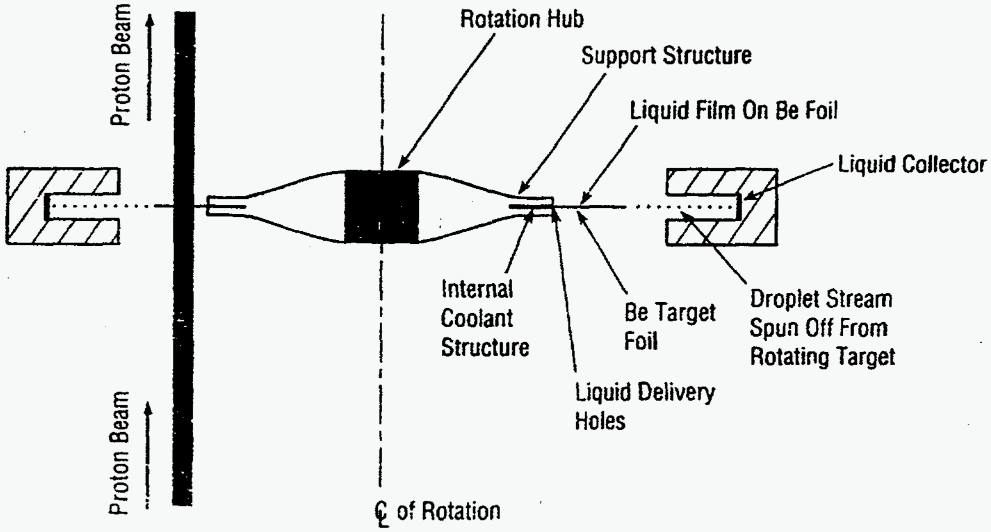

FIGURE 3
LIQUID FILM COOLING OF DISCOS TARGET

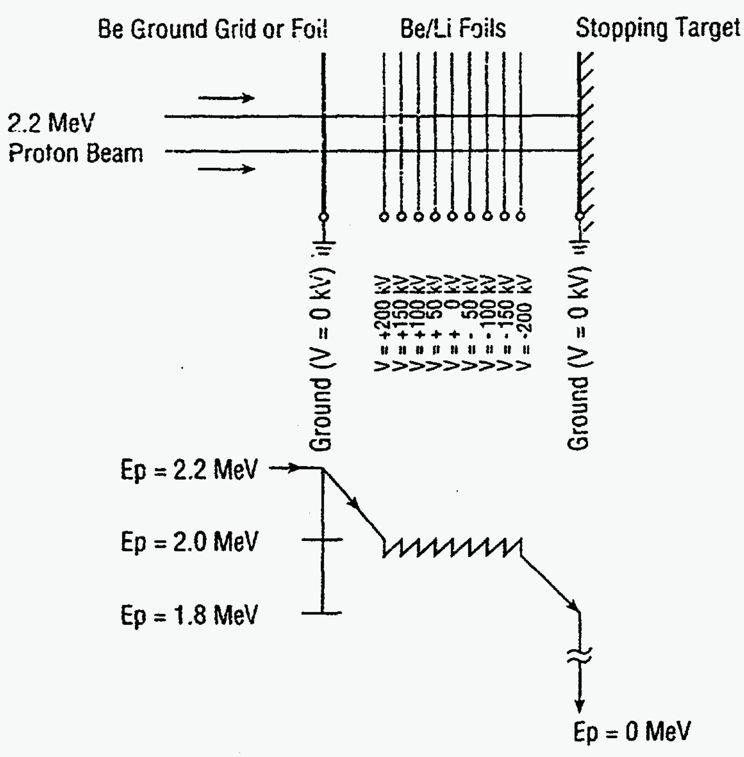

FIGURE 4
RE-ACCELERATION OF PROTON BEAM BY DC FIELDS BETWEEN
MULTIPLE FOILS/FILMS DISCOS TARGET

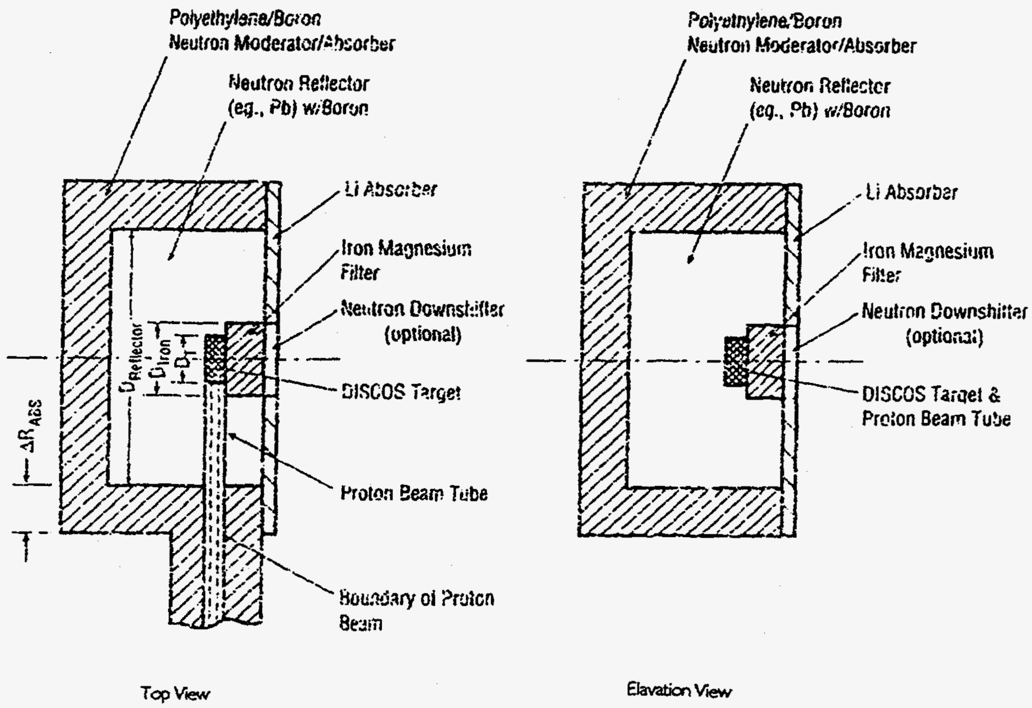

FIGURE 5
GEOMETRY FOR NIFTI/ DISCOS PRELIMINARY DESIGNS

Table I
Design Parameters for NIFTI/DISCOS Preliminary Designs

Iron/Magnesium Filter Layer	=	7.5 cm thick, 15 cm diameter
DISCOS Target Region	=	5 cm diameter, 10 cm long
Neutron Generating Region	=	2 cm diameter, 10 cm long
Type of Target	=	DISCOS Lithium Sheet
Proton Energy Range	=	1.904 to 1.889 MeV
Total Energy Added By DC Field	=	400 keV
Beam Tube Diameter	=	5 cm
Beam Diameter	=	2 cm
Reflector	=	Lead, 20 cm thick, 0.2% Boron
Outer Poly/Boron Absorber	=	10 cm thick, 5% Boron
Lithium Absorber on Front Face	=	2 cm thick Lithium Hydride

Table 2
Performance Parameters for NIFTI/DISCOS Preliminary Design

Proton Energy	1.9	1.9
1 cm "Down-shifter" Included	n	y
Fraction of Generated Neutron That Exit Through Beam Port	0.1894	0.1208
Average Energy of Neutron That Exit Thru Beam Port (keV)	18.4	11.6
Flux of Exiting Neutron per mA of Beam Current (n/cm^2 - mA)	5.74 (6)	3.66 (6)
Fraction of Neutron That Escape Through the Face Other Than the Beam Port	.0831	.0454
Total Neutron Fraction Escaping	.2140	.130
Photons Exiting Through Port per Neutron	.00234	.0134
Beam Current Required For 10^9 n/cm^2 - s at Port	175* / 2.2**	273 / 3.4

* 1 sheet DISCOS (5 keV energy loss)
** 80 sheet DISCOS (400 keV energy loss)

Table 3
Energy Spectra for Neutrons Escaping Through the Beam Port of NIFTI/DISCOS Preliminary Designs

(Proton Energy 1.9 MeV)

1 cm "Downshifter" Included	No	Yes
0 keV - 1 keV	9.384 (-3)	3.478 (-2)
1 keV - 10 keV	1.856 (-2)	2.734 (-2)
10 keV - 26 keV	7.709 (-2)	3.674 (-2)
26 keV - 50 keV	3.932 (-2)	1.110 (-2)
50 keV - 75 keV	4.349 (-2)	1.036 (-2)
75 keV - 100 keV	1.564 (-3)	4.516 (-4)
Total	1.894 (-1)	1.208 (-1)