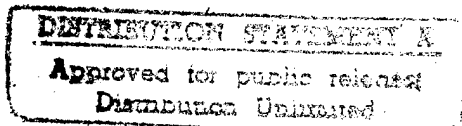


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NOTICE

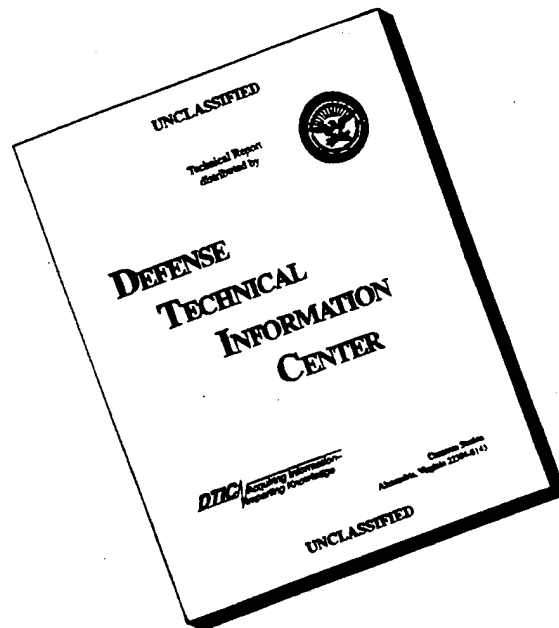
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FOCUSED PULSED NEUTRON SOURCE

BACKGROUND OF THE INVENTION

The present invention relates to a neutron source and, more particularly, to a focused pulsed neutron source that is particularly suited to produce low-energy neutron beams for Boron Neutron Capture Therapy (BNCT) of cancerous tissues.

5 In a BNCT treatment, a person with brain cancer is first injected with a boron compound that tends to localize in the cancerous tumors of the patient. The patient's head is then irradiated with a low-energy neutron beam. The boron absorbs ("captures") the neutrons, re-emitting a type of radiation that can
10 kill nearby tumor cells without harming healthy brain tissue. The energy level of the irradiating neutrons is critical because the neutrons should be powerful enough not to be stopped by the skull of the patient, but not so powerful as to damage tissue elsewhere. A non-reactor neutron source, that is, one that does not involve
15 radioactive material, is desired to be used for these medical applications because it can be relatively easily shielded so as to provide for a safe environment within the hospitals or other facilities performing the BNCT treatment.

 In a conventional non-reactor neutron source, charged
20 particles (e.g., from an ion source) are accelerated along a

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straight or curved trajectory and then collide with a target from which neutrons are emitted. There are two major problems limiting the useful neutron flux density from these types of neutron sources. The first problem is that the neutrons of these targets are emitted either isotropically or with a wide angle in the forward direction. Hence, the neutron flux density is reduced with distance from the neutron source as the function $1/R^2$. No neutron focus mechanism for focusing the neutron emission has been found to be effective operating in conjunction with these sources so that the spreading and reduction of neutron flux density remains a problem. The second problem is that in order to limit space charge effects, the ion beam, comprising the charged particles from the ion source, originates from a relatively small area of the ion source and manifests a relatively low current density. The total ion current provided by the small area is relatively low and the neutron flux is limited which makes impractical its usage in BNCT treatment. These two major problems need to be overcome in order to provide a non-reactor neutron source that develops a low-energy neutron beam that is particularly suited for BNCT treatment.

OBJECTS OF THE INVENTION

Accordingly, a primary object of the present invention is to provide a non-reactor neutron source that does not suffer the disadvantages of providing neutrons that are from a point or a small area either isotopically or at wide angle and correspondingly manifesting low flux density.

Another object of the present invention is to provide for a non-reactor neutron source that creates a low-energy neutron beam for the irradiation of cancerous tissues and that provides for a relatively uniform radiation dose throughout the cancerous tissues and reduces collateral damage to healthy tissues.

It is a further object of the present invention to provide a non-reactor neutron source having a converging high neutron flux that is particularly suited for medical applications.

A still further object of the present invention is to provide a low-energy neutron beam having a neutron fluence on a tumor that can be greater than 10^{12} neutron/cm² and is generated in a time scale of less than a second.

Further still, it is an object of the present invention to provide for a non-reactor neutron source having a selectable

Serial No. (Unassigned)
Inventors: Friedman et al.

Patents
Attorney Docket No. 76,526

geometry that produces low-energy neutron beams particularly suited for medical treatments.

SUMMARY OF THE INVENTION

5 The present invention is directed to a non-reactor neutron source having a convergent neutron flux which provides a low-energy neutron beam particularly suited for BNCT treatment.

10 The non-reactor neutron source comprises a source of ions, a target and, preferably, a moderator. The source of ions comprises a predetermined material with an emitting surface for launching ions and a predetermined shape having a geometric center. The target has a predetermined shape and is of a predetermined material that emits neutrons when reacting with the ions launched from the emitting surface. The target is located so as to be coaxial with and situated between the geometric center and the emitting surface of the source of ions. The moderator has a predetermined shape and is located so as to be coaxial with and situated between the geometric center and the target. The predetermined shape of the moderator, as well as the source of ions and the target, is either
15 cylindrical or spherical. The moderator comprises a material so that neutrons emitted by the target intercept the moderator and contain less energy as they exit the moderator than they had when
20

intercepting the moderator and have an energy level within a range of epithermal neutrons.

BRIEF DESCRIPTION OF THE DRAWINGS

5 These and other objects, features and advantages of the present invention, as well as the invention itself, will become better understood by reference to the following detailed description when considered in conjunction with the accompanying drawings, wherein the same reference numbers designate the same or corresponding parts throughout the several views, and wherein:

10 Fig. 1 is composed of Figs. 1(A), (B) and (C) which accumulatively make up a schematic of a triaxial ion diode serving as the source of ion of the non-reactor neutron source of the present invention.

15 Fig. 2 is a block diagram of the pulse source related to the present invention.

Fig. 3 is a schematic illustrating the operational aspects of triaxial ion diode of Fig. 1.

Fig. 4 is a partial schematic of one embodiment of the non-reactor neutron source of the present invention.

Fig. 5 is a schematic of a second embodiment of a non-neutron source of the present invention.

Fig. 6 is an iso-absorbed dose chart related to test data of the present invention.

5 Fig. 7 illustrates normalized thermal neutron doses related to the practice of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

10 With reference to the drawings, Fig. 1, composed of Figs. 1(A), (B) and (C), illustrates a triaxial ion diode 10 that serves as the source of ions for the non-reactor neutron source of the present invention devoid of radioactive materials and delivering low-energy neutron beams for the irradiation of cancer tissues in a manner known as a Boron Neutron Capture Therapy (BNCT) treatment.

15 Fig. 1(A) illustrates the triaxial ion diode 10 as having a centerline 12 which is also its geometric center. The geometric center 12 is of importance because the other elements comprising the non-reactor neutron source are arranged to be coaxial with the geometric center so that the neutron beam produced by the interaction of all of the elements is focused or radially converges
20 onto a selected target which is the cancerous tumor receiving the

BNCT treatment.

The triaxial ion diode 10 comprises a block of material 14 serving as a source of ions with an emitting surface for launching ions and having a predetermined shape. The source 14 of ions is held in place by an insulator 16. The source 14 of ions is encompassed on both sides by independent conductors 18 and 20 which are each connected to a ground potential 22. The source 14 of ions, also referred to herein as an electrode or anode, has means for being connected to a pulse source 24 that generates a high power pulse 26 causing ions, represented by directional arrows 28, to be emitted from the launching surface of the source 14 and accelerated radially inward as shown in Fig. 1(A). The predetermined shape of the triaxial ion diode may be either spherical, which produces a spherical distribution 30 of ions illustrated in Fig. 1(B), or cylindrical which produces a cylindrical distribution 32 of ions illustrated in Fig. 1(C). The ions 28 are generated in response to the application of the high power pulse 26 that is developed by the pulse source 24, which may be further described with reference to Fig. 2.

The pulse source 24 is of a conventional type and generates a pulse 26 having a duration in the range of about 0.1 to about 1.0 microseconds and produces sufficient energy so that the triaxial ion diode 10 provides for a source of ions that are emitted in a

beam comprised of charged particles having an energy level in the range from about 0.5 to about 5 MeV and comprising a current from about 100 to about 1000 kA. The pulse source 24 comprises a high voltage energy source 34, a Marx generator 36, a pulse forming line 38, and delay lines 40.

The high voltage energy source 34 may be comprised of capacitors which can store electrical energy at high voltages and which energy is delivered and responsive to the Marx generator 36 via signal path 42. The Marx generator 36, known in the art, may be replaced by a LC generator, a pulse transformer, or magnetic switches all of which, similar to the Marx generator, generate megavolt electric pulses of microsecond durations that are applied to the pulse forming line 38 via signal path 44.

The pulse forming line 38 may be a seven (7) ohm impedance Blumlein transmission line, known in the art, and provides an output, via signal path 46, to delay lines 40. The delay lines 40, known in the art, provide an output electrical pulse 26 preferably generated in the TEM coaxial mode, having a voltage level in the range from about 0.5 MV to about 5 MV and a current from about 100 to about 1000 kA. The pulse 26 is applied to the triaxial ion diode 10 whose operational aspects may be described with reference to Fig. 3.

The physics of intense ion sources, such as the triaxial ion diode 10, may be described using the simple geometry of two parallel surfaces 48 and 50 across which a high potential difference Voltage U, illustrated by box 52, is applied. The two surfaces 48 and 50 can freely emit electrons and ions. By solving Poisson's equation, one can find the maximum current density of electrons j_e^* (indicated by direction arrow 54) and of ions j_i^* (indicated by directional arrow 56) that flow between the two surfaces 48 and 50 and which may be represented by the below Expressions (1) and (2):

$$j_e^* = 1.86j_e \quad (1)$$

$$j_e = \frac{2^k}{9\pi} I_0 \frac{(U/(m_0c^2))^{3/2}}{d^2}$$

$$j_i^* = 1.86j_i \quad (2)$$

$$j_i = j_e (m_e/M)^k$$

In these Expressions (1) and (2), I_0 is a constant of a value of 17 kA, d is the separation between the two surfaces 48 and 50 and is herein termed the inter-electrode spacing, m_0 is the

electron mass, and M is the ion mass.

Since more electrons than ions are emitted (Expression 2), most of the electrical energy (about 93%) is in the electron component. To increase the amount of electrical energy transferred to the ions, the electron emission needs to be suppressed. In conventional ion sources, "cold" emission of charged particles is inhibited from the high voltage surfaces, and only ions that are externally injected can be accelerated. This is done by increasing the inter-electrode spacing, d , or alternatively by reducing the electric field on the metallic surfaces emitting charged particles. In these sources having a reduced electric field, the ion beam current density j_i^* is small due to space charge limitation (Expressions 1 and 2). It is desired that the ion beam current density j_i^* be increased so that it may serve the needs of BNCT treatment.

Ways to advantageously increase the ion current density have been discussed in the literature, see, for example, the technical article of V. M. Bystritskii and A. N. Dideenko, entitled "High Power Ion Beams" (in Russian) Energoatomizdat (1984), (translation) American Institute of Physics (1989), herein incorporated by reference. In the scheme described in this article, ions and electrons are freely emitted from the electrode surfaces but only the ions can flow without any restrictions across the inter-

electrode space d_1 , while the electrons are forced to reflex back and forth due to their own space charge or due to an external magnetic field applied parallel to the emitting surfaces. Assuming no loss mechanisms for electrons, a virtual cathode is formed at a distance $d' < d$ from the anode, and j_e^* is reduced considerably. On the other hand, the ion current density j_i^* is increased as may be shown by the use of Expression 2 after substituting d by d' . A non-reactor neutron system of the present invention incorporating the use of an external magnetic field is to be described hereinafter with reference to Fig. 5, whereas a non-reactor neutron system 58 illustrating the essential features of the present invention not having this magnetic field may be described with reference to Fig. 4.

In general, the non-reactor neutron source 58, schematically and partially illustrated in Fig. 4, provides a fluence of $>10^{12}$ neutrons/cm² on a cancerous tumor involved in the BNCT treatment, while minimizing the collateral damage to healthy tissues. The neutron source 58 uses a pulsed intense current of ions to generate fast neutrons. Using pulse power technology, one can generate pulses of ions with a particle energy of 0.5-5 MeV, a current of 100's kA and pulse durations of 0.1-1 microseconds. The ions 28, first illustrated in Fig. 1, are generated from a large area source of a cylindrical or spherical geometry realized by the triaxial ion diode 10 of Fig. 1. The ions 28 comprise either the spherical beam

distribution 30 of Fig. 1(B) or the cylindrical beam distribution 32 of Fig. 1(C), and are guided, more particularly, accelerated inward to a thin annular target 60 situated coaxially inside the ion-emitting surface of the triaxial ion diode 10.

5 The nuclear interaction between the target 60 nuclei and the bombarding ions launched from the emitting surface of the ion diode 10 produces a neutron "cloud" at the geometrical center of both the ion source 10 and target 60, that is, the centerline 62 of the triaxial ion diode 10 and the target 60. If desired, the material
10 of the target 60 may be selected to include a fissionable material that generates more than one neutron for each neutron that splits a nucleus when excited by the emitted ions 28. The fissionable material has a gain factor of $1/(1-k)$, where k is the prompt-neutron multiplication factor. The neutron source 58 has a
15 predetermined radius 64 measured from the centerline 62 to the emitting surface of the ion diode 10.

 The ions 28, launched from the ion emitting surface of the triaxial ion diode 10, interact with the material of the target 60 and generate fast neutrons 66. Moderator 68 moderates the neutrons
20 to epithermal energies which results in a three (3) dimensional irradiation pattern of thermal neutrons 70 that are almost uniformly distributed throughout a phantom, to be described with reference to Figs. 6 and 7, similar in dimension to a human brain

Serial No. (Unassigned)
Inventors: Friedman et al.

Patents
Attorney Docket No. 76,526

and generally indicated by reference number 72 and serving as a chamber located near centerline 62. A BNCT radiation >100 RAD can be generated by these thermal neutrons 70, during a single pulse, inside regions of the human brain that are loaded with 50 ppm of
5 boron.

The fast neutrons 66, created by the interaction caused by the bombardment of ions 28 of the target material 60, are too energetic to be very successful for BNCT treatment and need to be moderated to energy levels of 100 eV-10 keV which range defines epithermal
10 neutrons. The slowing down process is accomplished by the moderator 68 located to be coaxial with and situated between the geometric center 62 and the target 60. The moderator 68 comprises a material so that the fast neutrons 66 emitted by the target material 60 and intercepted the moderator 68 contain less energy as
15 they exit from the moderator 68 than they had when they intercepted the moderator 68. These slowed down neutrons serve as epithermal neutrons 70 particularly suited for BNCT treatment. The moderator 68 comprises a slab of material in which the fast neutrons 68 collide with atomic nuclei and lose their energy. The function of
20 the moderator 68 may also be provided by the use of a filter of "poison" material, known in the art, that absorbs neutrons at preselected energy ranges.

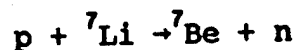
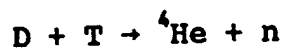
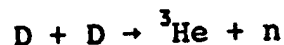
During the slow down process, provided by the moderator 68,

Serial No. (Unassigned)
Inventors: Friedman et al.

Patents
Attorney Docket No. 76,526

the direction of motion of the epithermal neutrons 70 become nearly isotropic. But, since the location of their slow down is close to the geometric center 62 of the ion source, that is, the triaxial ion diode 10, neutron reflectors known in the art comprising a material that scatter neutrons in a favorable direction, not shown in Fig. 4 but to be further described with reference to Fig. 5, are effective and may be used to direct a significant number of the epithermal neutrons 70 back to the central region of the chamber 72 so that they may intercept and treat the cancerous tissue being housed in the chamber 72. As seen in Fig. 4, the epithermal neutrons 70, generated in response to pulse 26, are focused onto the chamber 72 lodging the cancerous tumor that may receive the BNCT treatment.

The materials selected for the cylindrical block 14 of the triaxial ion diode 10 and for the target 60 determine the nuclear reaction encountered therebetween. The material of the cylindrical block 14 may be comprised of deuterium or other materials, known in the art, may be used. There are many nuclear reactions that could be used to generate neutrons and three such reactions are given below:



Each of the three reactions has a different cross section, a different energy threshold for the reaction to start, a different energy spectrum for emerging neutrons that depends on the angular distribution of the neutrons, and all of these properties are summarized in Table 1.

TABLE 1

REACTIONS	MAXIMUM CROSS SECTION σ (MILLIBARN)	ION ENERGY AT MAXIMUM σ (MeV)	NEUTRON ENERGY (MeV)	NEUTRON ANGULAR DISTRIBUTION
(1) $D+D \rightarrow {}^3\text{He}+n$	97	0.7	few MeV	$1 + A \cos^2(\theta)$
(2) $D+T \rightarrow {}^4\text{He}+n$	5000	0.12	14 MeV	isotropic
(3) $p+{}^7\text{Li} \rightarrow {}^7\text{Be}+n$	580	2.5	<1 MeV	$1 + B \cos(\theta)$

Choosing the ion species and a reaction to generate the desired neutron flux for BNCT treatment depends on many factors including: the voltage applied to the triaxial ion source (desired to be kept as low as possible), the cross section of the reactions, (desired to be as high as possible), the neutron energy of the epithermal neutrons (desired to be as low as possible), and the number of neutrons emitted in a forward direction with respect to the ion direction (desired to be as high as possible). We have determined that neutron production by an ion beam

comprising 100 kA of ion current for a 1 microsecond duration of pulse 26, yields 2×10^{13} neutrons/pulse for the reaction (2) of Table 1, and yields neutrons/pulse from about 4×10^{12} to about 5×10^{12} for the reactions of (1) and (3) of Table 1.

5 By selecting the material for the cylindrical block 14 of the triaxial ion diode 10 and the material for the target 60 so as to produce the reaction (3) of Table 1, one set of desired parameters for the triaxial ion diode 10 may be established. More particularly, it is desired that the triaxial ion diode 10 have a
10 relatively large diameter and a relatively large surface for emitting ions and be preferably operated so as to provide a beam comprised of protons having an energy level of 2.5 MeV. These protons, because of the geometry selected for the non-reactor neutron source 58, converge from many directions onto a target 60
15 which has an annular shape as shown in Fig. 4. Further, all of the devices, that is the triaxial ion diode 10, the target 60, and the moderator 68, all of Fig. 4, are preferably cylindrical in shape.

The ion source, that is, the triaxial ion diode 10, that operates at a voltage of 2.5 MeV and suppresses electron emission
20 by the selection of its inter-electrode spacing preferably desires an electric field on its metallic surface below 100 kV/cm, or, alternatively the inter-electrode spacing d of about 25 cm. The triaxial ion diode 10 desires a relatively large area so to

Serial No. (Unassigned)
Inventors: Friedman et al.

Patents
Attorney Docket No. 76,526

generate a relatively large ion current and the triaxial ion diode 10 desires a large radius to encompass components, such as the target 60 and the moderator 68 that down shifts (lowers energy) the neutron energy of the fast neutrons 66 emitted by the target 60.

5 For one embodiment, we selected one (1) meter (m) as the radius 64 of the emitting surface of the triaxial ion diode 10 and selected a length of emitting surface of the triaxial ion diode of 50 cm. For such parameters and by using Expressions 1 and 2, an ion current emitted by the triaxial ion diode 10 of the present

10 invention may be shown to have a value of 10 kA.

Many modifications may be made to increase the ion current and one of which is to be further described with reference to Fig. 5. A first way to increase ion current is to reduce the inter-electrode spacing d and apply a magnetic field parallel to the

15 electrodes to suppress electron motion, sometimes referred to as supplying magnetic insulation. The second way is to shape the magnetic field in such a manner that an electron cloud forms in proximity to the anode, that is, to the ion emitting surface of the triaxial ion diode 10. The first way increases the ion current by

20 a factor of 6 which may be verified by Expressions 1 and 2 by using a quantity $d = 10.0$ cm, as compared to the previous given quantity $d = 25$ cm. The second way increases the ion current by a factor >2 and smaller than 20. Hence, ion current exceeding 100 kA can be advantageously generated by the practice of the present invention.

A non-neutralized ion current, that is, current having the presence of space charge, of this magnitude (greater than 100 kA) is difficult to transport. The self-electric field, established by the space charge, residing in the beam produced by the triaxial ion diode 10 causes the beam to rapidly spread, commonly referred to as being "blown apart," over a relatively short distance. Reducing the self- electric fields may be achieved by allowing some of the electrons emitted from a virtual cathode or emitted from surfaces that are at a "negative" potential with respect to the electrode (that is, the material of the triaxial ion diode 10) to intercept and follow the ion trajectories but not to intercept the ion emitting area. The same magnetic field that prevents the electrons from reaching the anode (that is, the ion emitting surface of the triaxial ion diode 10) also guides some of the electrons emitted from the virtual cathode into the desired path of the ions. A system 74 which provides such a virtual cathode to reduce the self-electric fields and to increase the ion current of the triaxial ion diode 10 may be further described with reference to Fig. 5.

The non-reactor neutron source 74 of Fig. 5 comprises a cylindrical block of material 76 having a geometric center 78, also corresponding to the centerline of the neutron source 74, and one end 80 having a preselected portion 82 with opposite faces 84 and 86 of which surface 86 (not fully shown) serves as a launching surface for emitting ions also referred to as a high voltage (HV)

electrode or anode. The source 76 of ions has means for being connected to the pulse source, in particular, to the pulse 26 previously described with reference to Figs. 1, 2 and 4. The source 76 of ions and first and second cylindrical conductors 88 and 90 comprise the triaxial ion diode of the present invention of
5 the non-reactor neutron source 74.

The first and second cylindrical conductors 88 and 90 are coaxial with the source 76 of ions and are each separated from the source 76 of ions by a predetermined distance d and each has means
10 for being connected to a ground potential 92. The second conductor 90 has a major surface, consisting of sections 94 and 96, and a minor portion 98. The sections 94 and 96 are arranged so as to be situated between the geometric center 78 and the source 76 of ions. The major portion, comprising sections 94 and 96, is arranged to
15 provide an opening 100 located proximate to the surface 86 for emitting ions and serves as a passageway. The passageway 100 has an interior 102 carrying a material 104 a predetermined distance on its walls and which material serves as an electron emitter. The minor portion 98 has an extension portion 106 also serving as an
20 electron emitter located proximate the major portion, more particularly, section 96, but not proximate the passageway 100.

The non-reactor neutron source 74 further comprises means 108 for reducing and directing neutron energy which is located in the

interior of the passageway 100 near the end of the material 104 serving as an electron emitter and is situated between the source 76 of ions and the geometric center 78. The means 108 for reducing and directing neutron energy has a mouth 110 that faces the opening
5 of the passageway 100 and which leads into a cavity 112 having a bottom 114 as shown in Fig. 5.

The means 108 for reducing and directing neutron energy may comprise a moderator comprising a material such as that of the moderator 68 of Fig. 4. Similarly, the moderator may be comprised
10 of the "poison" material that absorbs neutrons at preselected energy levels as previously discussed with reference to Fig. 4. Furthermore, the means 108 for reducing and directing neutron energy may comprise a reflector made up of material so that the neutrons that strike the reflector are scattered in a preferential
15 direction as they exit from the reflector.

A target 116, similar to the material of target 60 of Fig. 4 and preferably comprising the fissionable material, rests on the bottom 114 of the cavity 112. The material of the target 116, the material of the source 76 of ions, as well as the material of the
20 means 108 for reducing and directing neutron energy, are all selected so as to produce epithermal neutrons 118 that intercept a chamber 120 that is similar to the chamber 72 of Fig. 4 and which is located near and coaxial with the geometric center 78. The

chamber 120 is situated between the geometric center 78 and the means 108 for reducing and directing neutron energy.

The non-reactor neutron source 74 further includes a configuration 122 comprising magnetic field coils arranged as shown in Fig. 5 into groups 122A, 122B, 122C. The group 122A is wrapped so as to cover the first conductor 88 encompassing at least the face 84 of the cylindrical block 76 not serving as a source for emitting ions. The groups 122B and 122C are wrapped so as to cover the major portion consisting of sections 94 and 96 of the second conductor 90 on both sides of the passageway 100.

The configuration 122 of magnetic field coils is selected so that the surface 86 of the selected portion 82 that is desired for emitting electrons is preferentially excited when a pulse 26 is generated by the pulse source 24. The emitted ions from surface 86 are radially directed and accelerated inward into a beam 124 that enters into the mouth 110 of the means 108 for reducing and directing the neutron energy and has a nadir that corresponds to the bottom 114 of the cavity 112 so as to intercept the target 116. As seen in Fig. 5, the ion beam 124, generated in response to the pulse 26, is focused on the target 116 which, in turn, generates the epithermal neutrons 118 that are focused on the chamber 120 lodging the cancerous tumor that may receive the BNCT treatment. As further seen in Fig. 5, the ion beam 124 has an upwardly bowed

Serial No. (Unassigned)
Inventors: Friedman et al.

Patents
Attorney Docket No. 76,526

portion 124A that serves as the virtual cathode generated by the electron emitters 104 and 106 and that intersect and follow the ion trajectories represented by the ion beam 124.

5 It should now be appreciated that the practice of the present invention provides for non-reactor neutron sources that develop relatively large ion currents and provide the focusing effects for the epithermal neutrons that is achieved by using a source geometry comprising either a cylindrical or spherical shape. The ions represented by charged particles are emitted from a relatively
10 large area extended source of the triaxial ion diode and are accelerated rapidly inward to collide with a target situated coaxial with the triaxial ion diode. The interaction between the ions and material of the target generates fast neutrons whose energy is retarded by a moderator so as to develop the desired
15 epithermal neutrons used for the BNCT treatment.

EXPERIMENTAL TESTING RELATED TO THE NEUTRON SOURCE OF THE PRESENT INVENTION

In a recently reported experiment some aspects of BNCT dosimetry were investigated. The experiments were reported by N. Gupta et al, in a technical paper entitled "Effect of Head Phantom
20 Size on ^{10}B and $^1_0\text{H}[n,\gamma]^2_1\text{H}$ Dose Distributions for a Broad Field

Serial No. (Unassigned)
Inventors: Friedman et al.

Patents
Attorney Docket No. 76,526

Accelerator Epithermal Neutron Source for BNCT," published in
Medical Physics 398, 20 (1993), and herein incorporated by
reference. In this experiment, neutrons were generated from the
interaction between a 2.5 MeV proton beam and a Li target. The
5 fast neutrons resulting from such interaction were moderated to
epithermal energy and then entered into a rectangular parallelepiped
water filled head phantom. The phantom dimensions were 17x17x15
cm, simulating a "large brain size." The epithermal neutrons
emanated from a moderator area defined by a 36.5 cm diameter, but
10 in general followed the direction of the proton beam. A boron-
fluorine detector of small dimensions was moved inside the head
phantom to measure the spatial dose distribution of thermal
neutrons. The experimental results, to be further discussed with
reference to Figs. 6 and 7, showed that the epithermal neutrons
15 from a single proton beam deliver a much lower thermal neutron dose
at the center of a large brain than at a depth thereof of 3 cm.

In the practice of our invention, we used the data from the
single neutron source experiment of Gupta et al. to calculate the
BNCT dose expected if the same epithermal neutron distribution was
20 directed at a similar size phantom from the full 360° of azimuthal
directions (cylindrically symmetric source) similar to that
obtainable from either of the embodiments of Figs. 4 and 5. For
the calculations of our experiments, we used a cylindrical head
phantom with a 17 cm diameter (e.g., radius 64 of Fig. 4 = 8.5 cm)

and a 17 cm length of emitting surface for launching ions similar to that of the triaxial ion diode of either Figs. 4 or 5. Since the ion source, the target, the moderator and the phantom share a common axis, as shown in either embodiment of Figs. 4 and 5, the thermal neutron density, such as that provided by the epithermal neutrons of the present invention, inside the phantom is constant along any circle around this axis. The results of our calculations for our experiments may be further described with reference to Fig. 6.

10 Fig. 6 shows an iso-absorbed dose chart illustrating the calculated relative dose contours yielded by using a multi-directional neutron source, such as that obtained from either embodiment of Figs. 4 or 5. More particularly, Fig. 6 shows the dose contours yielded from epithermal neutrons, such as those
15 identified by reference number 70 of Fig. 4 or those identified by reference number 118 of Fig. 5, respectively intercepting the chamber 72 of Fig. 5 or the chamber 120 of Fig. 6 either of which chamber may lodge a cancerous tissue for treatment by the BNCT procedure. The epithermal neutrons 70 or 118 create a neutron
20 fluence on the tumor, comprised of the cancerous tissue, that can be a dosage of advantageously more than 10^{12} neutrons/cm². Specifically, Fig. 6 shows a relatively constant dose created by the epithermal neutrons 70 or 116 starting at 80 near the center (identified by either reference number 62 (Fig. 4) or 78 (Fig. 5)),

and moving upward to 90 as the distribution of the dosage move toward the outer perimeter defined by the radius 64 (Fig. 4). The distribution of the dosage provided by the present invention may be further described with reference to Fig. 7.

5 Fig. 7 has a X axis indicated as the radial distance, such as that of radius 64 of Fig. 4, from the center, such as that of center 62 of Fig. 4, given in cm. Fig. 7 also has a Y axis indicating the normalized thermal neutron dose created by epithermal neutrons, such as the epithermal neutrons 70 of Fig. 4.
10 The epithermal neutrons 70 enter the head phantom at a distance of about 8.5 cm from the center of the head phantom, indicated as 0 on the X axis of Fig. 7.

 Fig. 7 has a first curve 126 comprising a plurality of triangles and a second curve 128 comprising a plurality of squares.
15 Fig. 7 shows two BNCT doses along a line intersecting the center of the head phantom of Fig. 6. The first curve 126 is the data obtained from the unidirectional neutron source experiment of N. Gupta et al. and the second curve 128 is the calculated results from the multi-directional neutron source, such as that obtainable
20 from the embodiments of Figs. 4 and 5. In the first case, represented by curve 126, the thermal neutron dose reached a maximum at around 3 cm from the place of entry and then fell off by a factor of 3 at a depth of 8.5 cm (the center). However, in the

Serial No. (Unassigned)
Inventors: Friedman et al.

Patents
Attorney Docket No. 76,526

second case, represented by curve 128 obtainable by the practice of the present invention, the dose dropped by only 25% at a depth of 8.5 cm. A comparison between curves 126 and 128 reveals the curve 128 of the present invention provides a relatively uniform thermal
5 neutron dose as compared to that obtainable from the prior art illustrated by curve 126. The relatively uniform dose has the benefits of uniformly treating the cancerous tissues and avoiding straying into healthy tissues that might otherwise damage these healthy tissues.

10 It should, therefore, be readily understood that many modifications and variations of the present invention are possible.

It is, therefore, to
be understood that the
invention may be practiced otherwise than as specifically
15 described.

Serial No. (Unassigned)
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Patents
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ABSTRACT OF THE DISCLOSURE

A non-reactor neutron source is disclosed that allows for a pulse intense current of ions to generate neutrons that are epithermal neutrons and provide low-energy neutron energy particularly suited for Boron Neutron Capture Therapy (BNCT) treatment. The present invention provides for a neutron fluence on a tumor which can be more than 10^{12} neutrons/cm² and is generated into a time scale of less than 1 second. The radiation dose provided by the present invention is focused yet uniformly distributed so as to attack cancerous tissues and reduce collateral damage to healthy tissues.

PATENT 76,526
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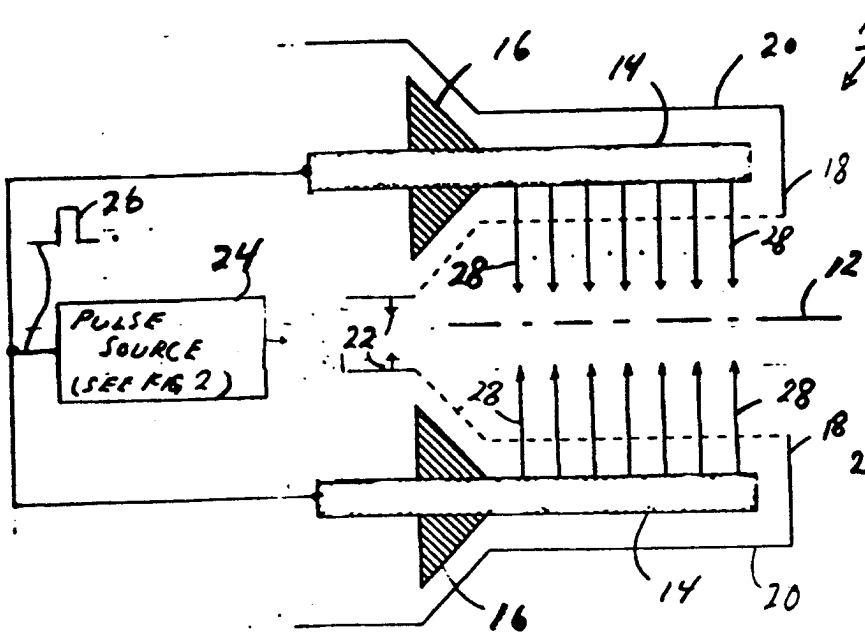


FIG 1 (A)

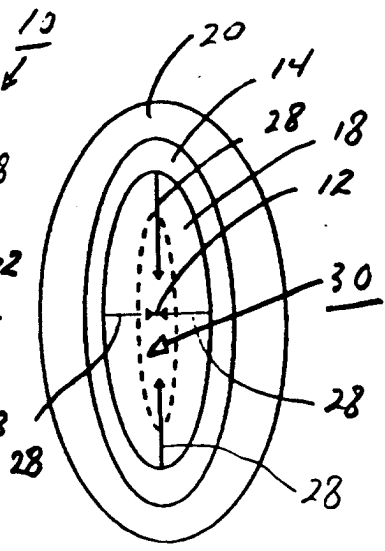


FIG 1 (B)

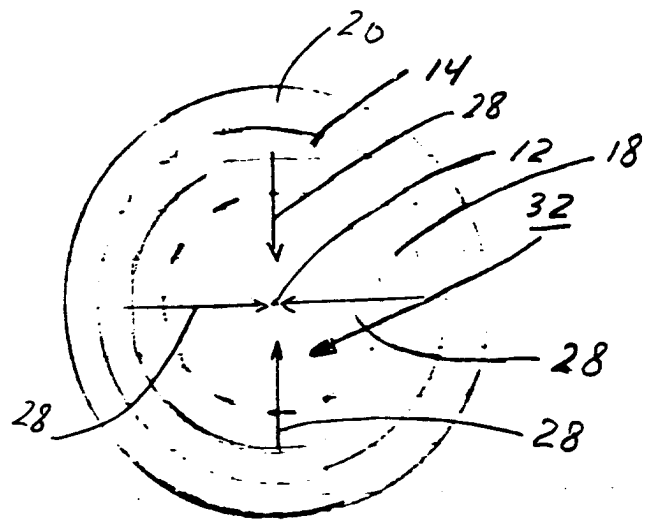


FIG 1 (C)

FIG 1

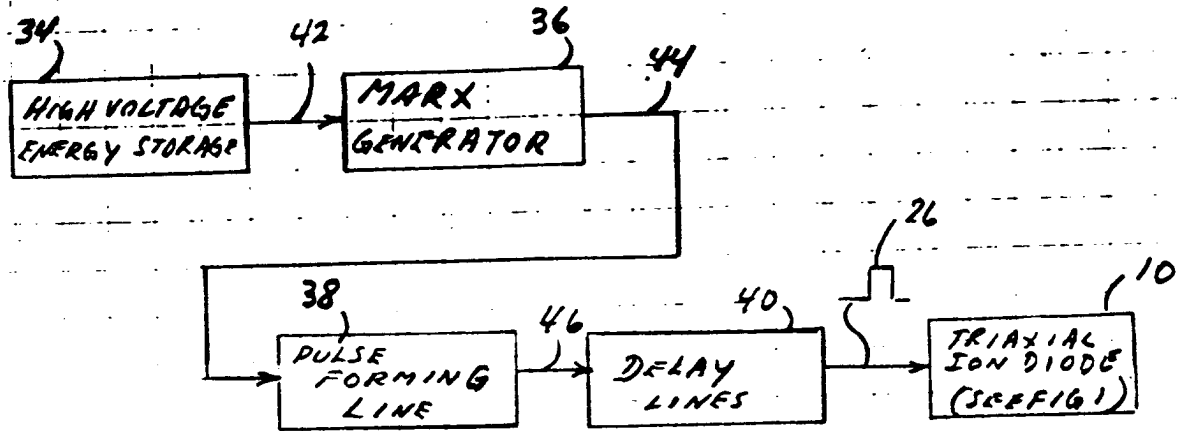


FIG 2

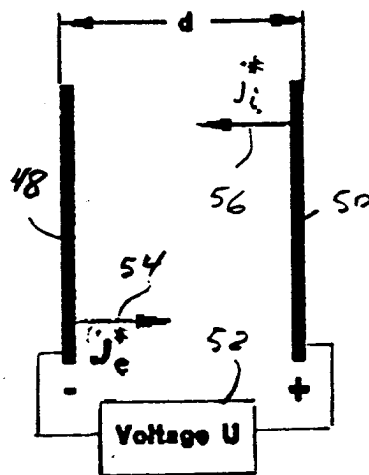


FIG 3

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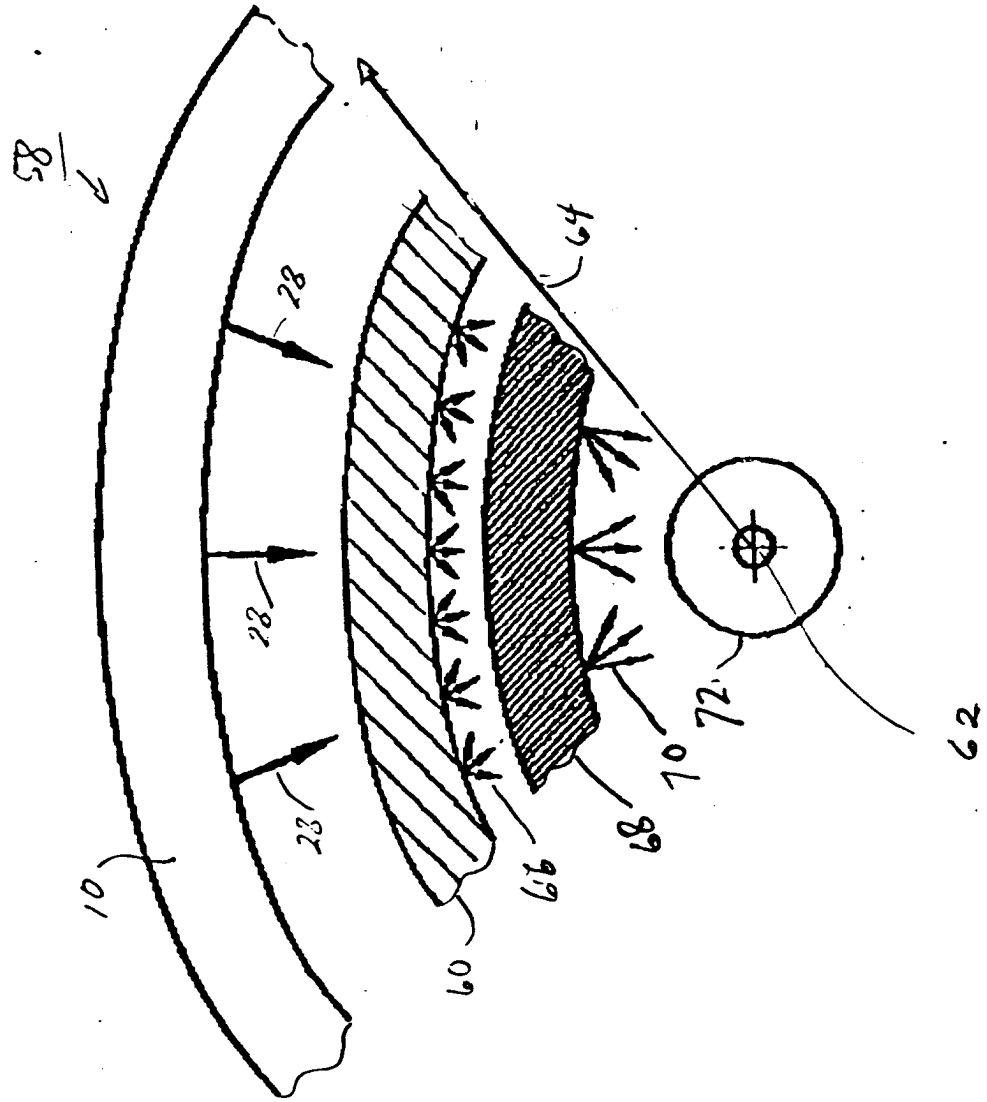


FIG. 4

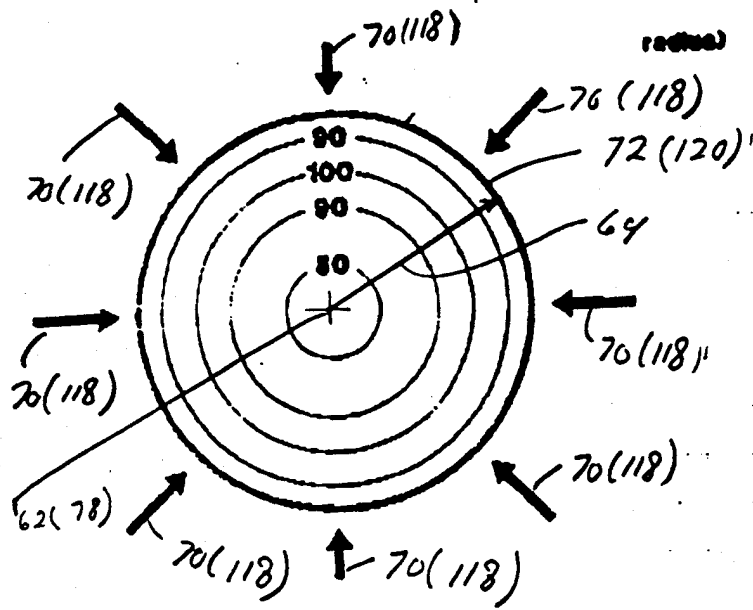


FIG 6

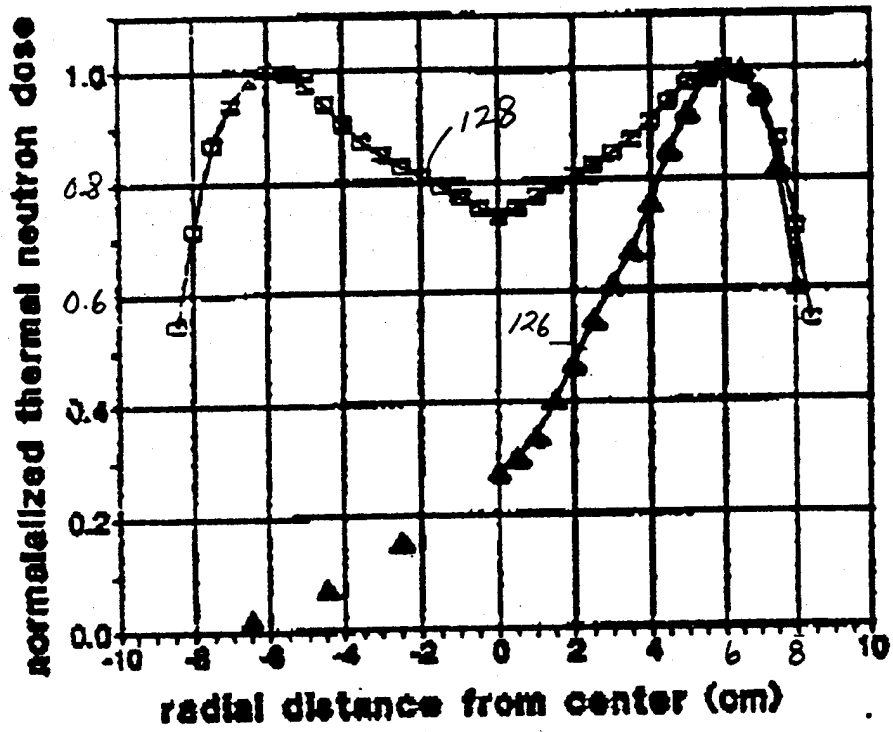


FIG 7