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(54) **SCANNING APERTURE ION BEAM
MODULATOR**

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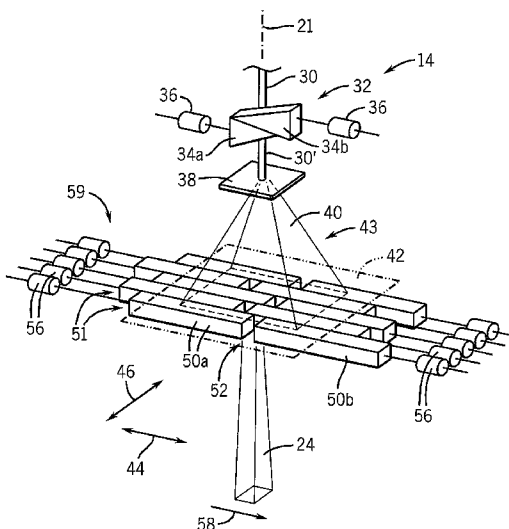
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(57) **ABSTRACT**

A modulator for ions such as protons employs multiple shutter pairs to create independently movable apertures effecting a multiple pencil beam treatment of the patient thereby increasing treatment speed by eliminating the need for a custom compensator.

25 Claims, 4 Drawing Sheets



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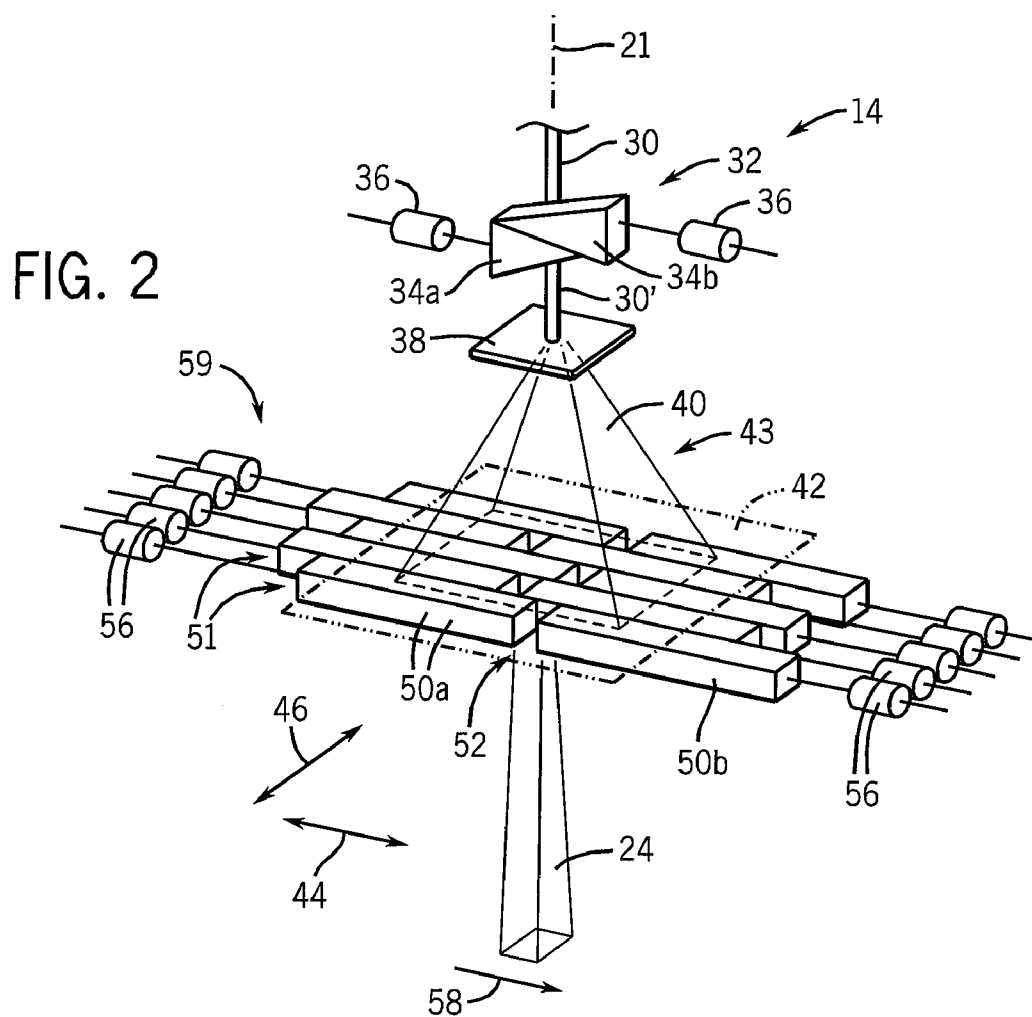
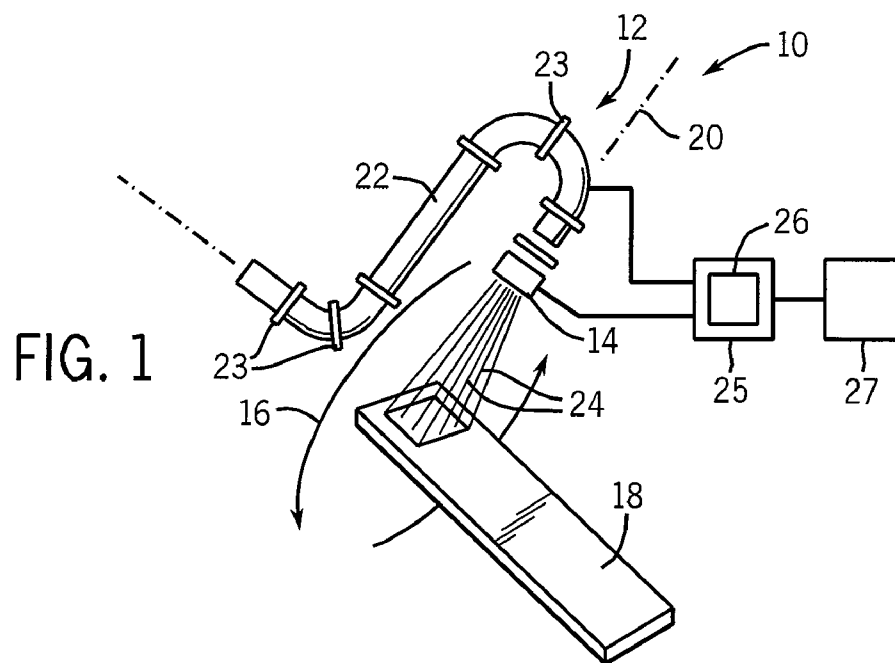
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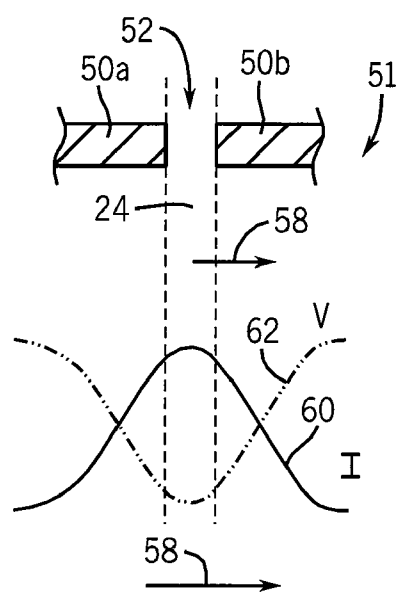


FIG. 3

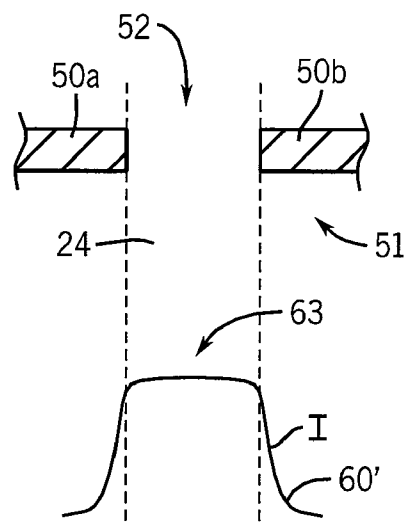


FIG. 4

FIG. 5

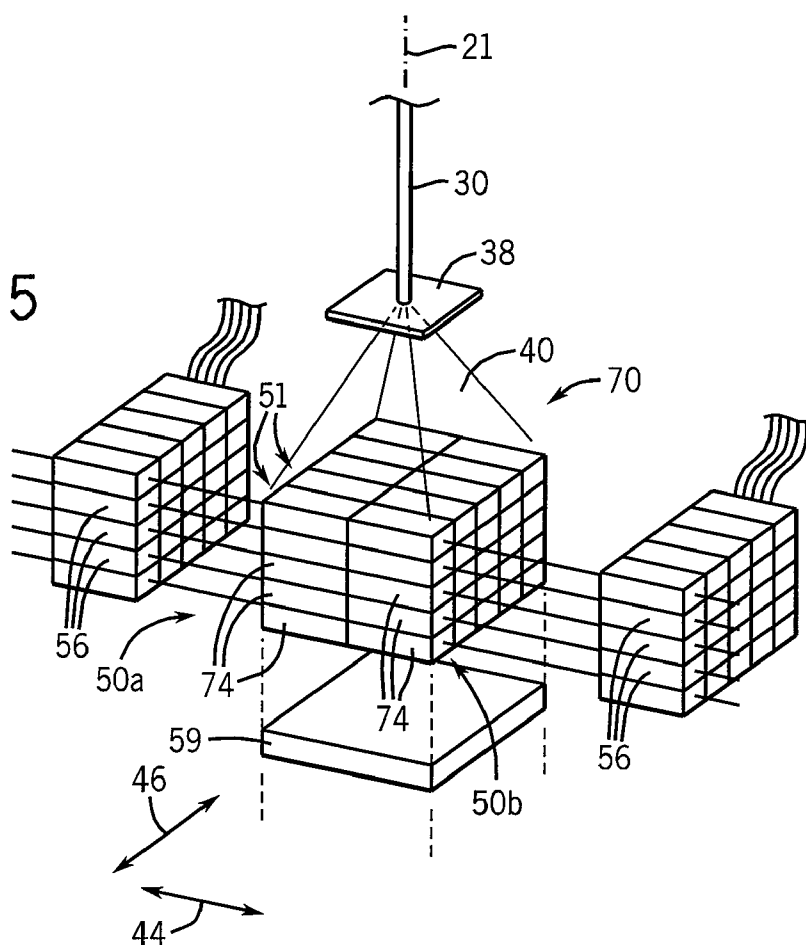


FIG. 6

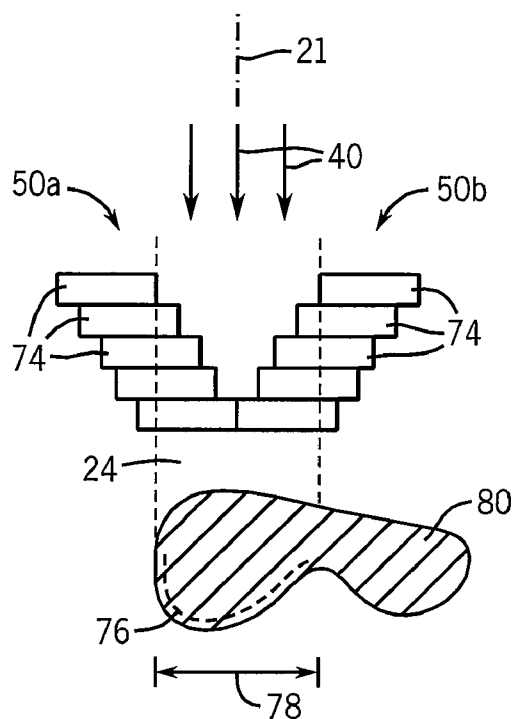


FIG. 7

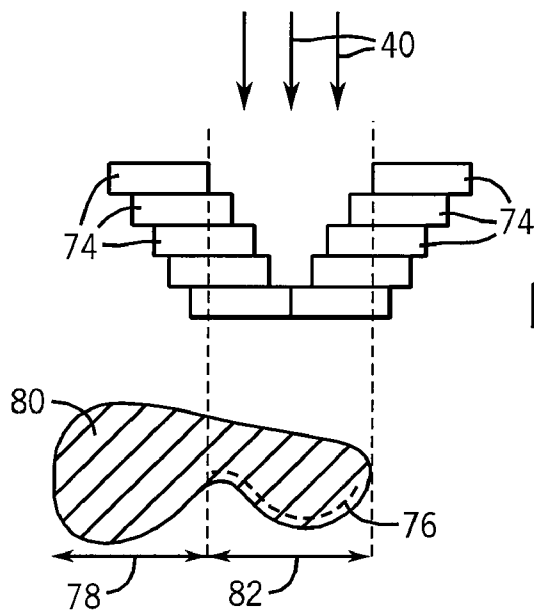


FIG. 8

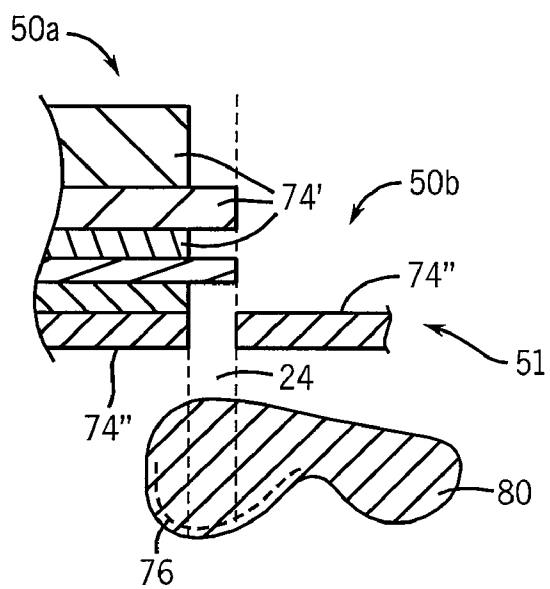
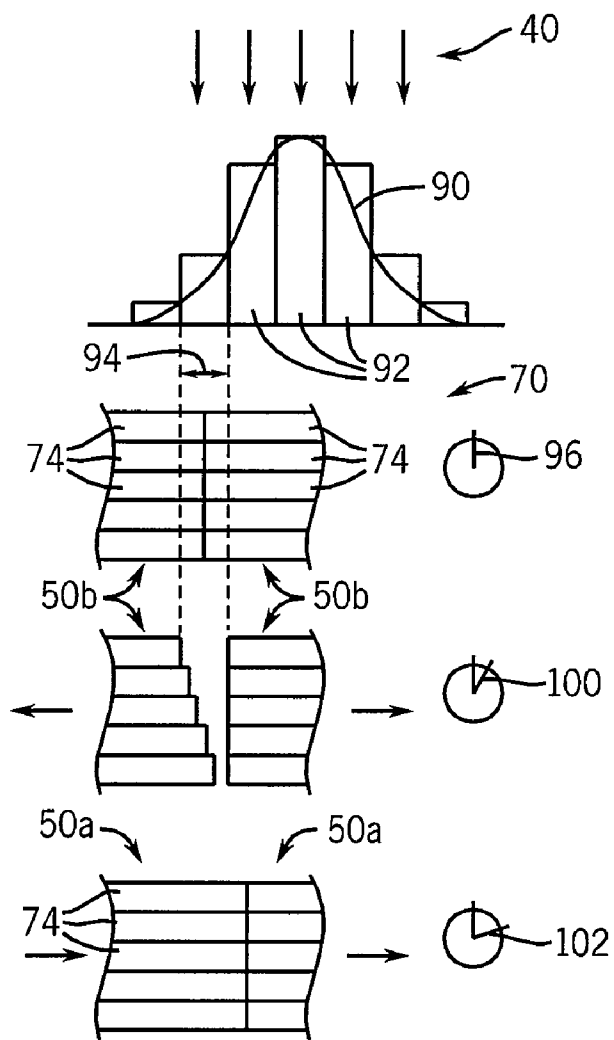


FIG. 9



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SCANNING APERTURE ION BEAM MODULATOR

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application 60/891,859, filed Feb. 27, 2007, and PCT Application PCT/US2008/055090, filed Feb. 27, 2008, the disclosures of which are incorporated herein by reference.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with United States government support awarded by the following agency: NIH CA088960. The United States has certain rights in this invention.

BACKGROUND OF THE INVENTION

The present invention relates to radiation therapy systems using ions, such as protons, for the treatment of cancer and the like and, in particular, to a system providing improved modulation of an ion beam.

External beam radiation therapy may treat a tumor within the patient by directing high-energy radiation in one or more beams toward the tumor. Recent advanced external beam radiation systems, for example, as manufactured by Tomotherapy, Inc., treat a tumor with multiple x-ray fan beams directed at the patient over an angular range of 360°. Each of the beams is comprised of individually modulated beamlets whose intensities can be controlled so that the combined effect of the beamlets, over the range of angles, allows an arbitrarily complex treatment area to be irradiated.

X-rays deposit energy in tissue along the entire path between the x-ray source and the exit point in the patient. While judicious selection of the angles and intensities of the x-ray beamlets can minimize radiation applied to healthy tissue outside of the tumor, inevitability of irradiating healthy tissue along the path to the tumor has suggested the use of ions such as protons as a substitute for x-ray radiation. Unlike x-rays, protons may be controlled to stop within the tissue, reducing or eliminating exit dose through healthy tissue on the far side of the tumor. Further, the dose deposited by a proton beam is not uniform along the entrance path of the beam, but rises substantially to a “Bragg peak” near a point where the proton beam stops within the tissue. The placement of Bragg peaks inside the tumor allows for improved sparing of normal tissue for proton treatments relative to x-ray treatments.

Unlike photon (e.g. x-ray) radiation therapy, radiation therapy with protons or other ions allows separate control of intensity (i.e., the number of protons per second within an area) and energy (i.e., the speed of the protons). Control of the intensity and time of exposure determines the total dose delivered by the protons to tissue, while control of the energy of the protons, by virtue of the Bragg peak described above, controls the depth of the exposure within the tissue.

Current proton therapy systems adopt one of two general approaches. In the first approach, the proton beam is expanded to subtend the entire tumor and the energy of the protons, and hence their stopping point in the tissue, is spread in range, to roughly match the tumor depth. Precise shaping of the exposure volume is provided by a specially constructed range correction compensator which provides additional range shifting to conform the distal edge of the beam to the distal edge of the tumor. This treatment approach essentially

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treats the entire tumor at once and, thus, is fast and yet less precise and requires the construction of a special compensator.

In a second approach, the proton beam remains narrowly collimated in a “pencil beam” and is steered in angle and adjusted in range to deposit the dose as a small spot within the patient. The spot is moved through the tumor in successive exposures until an arbitrary tumor volume has been irradiated. This approach is potentially very accurate, but because the tumor is treated in successive exposures, is slower than the first approach. Further the small spot sizes create the risk of uneven dose placement or “cold spots” should there be patient movement between exposures.

The complexity of these techniques normally limits the treatment to a single or small number of angles about the patient. This can reduce the level of conformity of the radiation dose to the target tumor because of this strong asymmetry of the Bragg peak of the protons.

BRIEF SUMMARY OF THE INVENTION

The present invention provides the benefit of a scanning pencil beam while greatly increasing treatment speed. This is done by using a beam modulator that takes an area beam (as opposed to a pencil beam) and effectively creates multiple independent pencil beams that may simultaneously treat the patient. The modulator may independently control both intensity and energy of each pencil beam, reducing or eliminating the need for a custom compensator.

Specifically the present invention employs an area beam of ions directed along an axis and having a longitudinal and latitudinal extent in cross-section. The area beam is controllably occluded with a set of longitudinally opposed latitudinally adjacent shutter pairs, each shutter of each pair controllable and extendable to different longitudinal distances. The shutters may thus simultaneously control multiple discrete beams, which are actually portions of the area ion beam, at different adjacent latitudinal positions with controllably independent longitudinal positions. The shutters may control either or both the intensity and energy of the ion beams.

It is thus an object of one embodiment of the invention to increase the treatment speed of the patient by using multiple, independently controllable beams.

Each shutter pair may comprise opposed shutters that can fully block the ion beam from passing through the shutter. The shutter pairs can be moved to control a dwell time of an aperture formed between the shutters to control the intensity of the ion beam at a variety of longitudinal locations.

It is thus one object of one embodiment of the invention to provide a method of operating shutters to independently control the intensity of the separate ion beams.

The shutter pairs may be controlled to move a center of an aperture created between the shutter pairs and to change a longitudinal separation between the shutter pairs.

It is thus an object of one embodiment of the invention to permit control of the longitudinal dimension of each ion beam independently from its longitudinal position. In this way longitudinally adjacent areas of the patient requiring identical or similar intensities may be simultaneously treated further reducing treatment time.

Each shutter may be constructed of multiple blades, each sized to only partially block the ion beam from passing through the blade. The multiple blades may be independently adjusted to control an amount of overlap among the blades and a longitudinal location of the overlap to in turn control the energy of the ion beam at a variety of longitudinal locations.

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It is thus an object of one embodiment of the invention to provide a method of simultaneously controlling the energy of the multiple independent ion beams.

The multiple blades of each shutter pair when fully overlapping along an axis of the ion beam may fully block passage of the ion beam, and the multiple blades of each shutter pair may be further controlled to control a dwell time of an aperture formed between the multiple blades to control the intensity of the ion beam at a variety of longitudinal locations.

It is thus an object of one embodiment of the invention to provide a system that may control both the energy and intensity of multiple simultaneous beams.

The area beam may have a non-uniform intensity distribution and the dwell time may be controlled according to the non-uniform intensity distribution and the desired treatment intensity to correct for the non-uniform intensity distribution.

It is thus another object of one embodiment of the invention to permit the generation of an area beam having lower uniformity to reduce the generation of undesired neutrons.

The blades of each shutter pair have equal thicknesses.

It is thus an object of one embodiment of the invention to provide a shutter system that may implement in a piecewise fashion an arbitrary attenuating compensator. The equal thickness shutters allow a complex, energy profile to be developed. The term "equal thickness" is intended to include shutters of different materials and different thickness so as to operate as if they were of equal thicknesses of a single material.

Alternatively the blades of each shutter pair may have different according to a binary sequence.

It is thus an object of one embodiment of the invention to provide the high resolution in energy control with a limited number of blades.

The area beam may be rotated about a patient to provide treatment of the patient at a plurality of angles.

It is thus an object of one embodiment of the invention to provide a system that has suitable speed to permit a large number of angles of patient treatment to be practical.

These particular features and advantages may apply to only some embodiments falling within the claims and thus do not define the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a simplified representation of a proton therapy machine suitable for use with the present invention and having a rotating gantry and a modulator directing multiple independent pencil beams of protons toward a patient support at a range of angles;

FIG. 2 is an exploded isometric representation of a first embodiment of the modulator using multiple, ion-opaque modulation elements for controlling the intensity of the individual pencil beams;

FIG. 3 is a side elevational view of one modulation element showing movement of a shutter pair for intensity modulation;

FIG. 4 is a figure similar to that of FIG. 3 showing the movement of the shutter pair for beam width control;

FIG. 5 is a figure similar to that of FIG. 2 showing a second embodiment of the modulator having multiple, energy attenuating modulation elements for controlling the energy of the individual pencil beams and optionally including the modulator of FIG. 2;

FIG. 6 is a figure similar to that of FIG. 3 showing one shutter of the modulation element of FIG. 5 composed of blades having equal thickness and used to create a piecewise compensator for a tumor;

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FIG. 7 is a figure similar to that of FIG. 6 showing a shifting of the blades of the modulator element with respect to FIG. 6 for creation of the piecewise compensator;

FIG. 8 is a figure similar to that of FIG. 6 showing blades with varying thickness used for energy control of a pencil beam; and

FIG. 9 is a side elevational view of an intensity variation along a longitudinal axis through the area beam and showing use of the blades of FIG. 6 for both intensity and energy control according to the variable intensity of the area beam.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to FIG. 1, a proton therapy machine 10 may include a gantry 12 having a modulator 14, both of which may orbit 16 about a patient (not shown) who is supported on a patient support table 18.

The modulator 14 receives a source of protons from a proton source conduit 22 that may conduct protons from a synchrotron, cyclotron or the like and, by means of bending magnets 23, direct them toward the patient support table 18 at all positions within the orbit 16.

The protons from the proton source conduit 22 will generally be narrowly collimated to a pencil beam (not shown) when received by the modulator 14. The modulator 14 spreads the pencil beam into an area beam radiating along an axis 20, and individually modulates independently positionable beamlets 24 (e.g., pencil beams) in energy and intensity. The beamlets 24 are controlled by a control computer 25 communicating with the modulator 14, the control computer 25 executing a stored program 26 to provide control signals to the modulator 14 according to stored treatment sinograms 27 indicating desired intensities and energies of the individual beamlets 24 as a function of the angle of the gantry 12 in orbit 16.

Referring now to FIG. 2, in a first embodiment, the modulator 14 receives a pencil beam 30 along axis 21 and directs it to an energy modulator 32, in this case, being a pair of opposed wedges 34a and 34b. These two wedges 34a and 34b overlap to present a rectangular cross-section within the beam 30. The amount of overlap, and thus the thickness of the cross-section, is controlled by moving the wedges 34a and 34b to increasing or decreasing overlap by means of electrically controlled actuators 36, the latter receiving signals from computer 25. The thickness of wedge material within the beam 30 controls the energy of the proton in the exiting energy modulated pencil beam 30'. An alternative energy modulator (not shown) is a dielectric wall accelerator which can adjust the acceleration of the ions electrically thus eliminating the neutron production incident to systems that reduce energy of an existing ion beam.

The energy modulated pencil beam 30' may next be received by a scattering foil 38 which spreads the pencil beam 30' into an area beam 40. The area beam 40 radiates along axis 21 spreading in a longitudinal extent 44 and a latitudinal extent 46. Normally the latitudinal extent 46 will be parallel to an axis of the orbit 16, however the opposite orientation with the longitudinal extent 44 parallel with the axis of the orbit 16 may also be used.

The area beam 40 may be masked to a rectangular cross-sectional area 43 by collimator 42 to be received by an area modulator 59 including a set of shutter pairs 51 forming independent modulation elements. The shutter pairs 51 are latitudinally adjacent to each other so that when the shutters are closed (as will be described) they fully fill the cross-sectional area 43.

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Each shutter pair **51** includes a left and right shutter **50a** and **50b**, respectively, the shutters **50a** and **50b** extending longitudinally and independently movable in the longitudinal direction toward and away to define a controllable aperture **52** therebetween. The aperture **52** thus formed may be controlled in longitudinal width and longitudinal center-point location.

Generally, each shutter **50a** and **50b** will be opaque to the proton beam, blocking all radiation except that passing through the aperture **52** as beamlet **24**. Accordingly, the shutter pairs **51** together convert the area beam **40** into a plurality of independently controllable beamlets **24** corresponding to each aperture **52**. In operation the apertures **52**, and hence the beamlets **24**, will be scanned longitudinally as indicated by direction arrow **58**.

The position of each shutter **50a** and **50b** is controlled by a respective actuator **56** electrically communicating with the computer **25**.

Referring now also to FIG. 3, by moving the shutters **50a** and **50b** for each shutter pair **51** along direction arrow **58** and controlling the velocity **62** of longitudinal movement of the aperture **52**, the average intensity **60** of radiation directed toward the patient from the beamlet **24** (during the treatment) may be controlled as inversely related to the velocity **62**. Thus, when the beamlet **24** dwells for a longer period of time at a given longitudinal position, the total proton flux, and thus dose, increases correspondingly.

It will be understood that multiple beamlets **24** generated by the modulator **14** may have their scanning speed independently controlled to independently control the dose delivered by each of the beamlets **24**. This control may be done in parallel so treatment by each beamlet **24** may occur simultaneously.

Referring now to FIG. 4, the ability to move the shutters **50a** and **50b** independently also allows the longitudinal size of the aperture **52** to be changed. This allows widening the aperture when longitudinally adjacent portions of the tumor require identical treatment resulting in a greater efficiency of treatment. For example if an intensity **60'** has a plateau portion **63** with essentially constant longitudinal intensity, the beamlet **24** may be widened to equal the width of this plateau portion **63**, decreasing treatment time over that which would be required by separate sequential treatments using narrower beamlets **24**.

Referring now to FIG. 5, in an alternative embodiment, the energy modulator **32** may be eliminated and the pencil beam **30** may be received directly by a scattering foil **38** (or the like) to generate the area beam **40**. The area beam **40** may then be received (after collimation to a rectangular area by collimator **42**, not shown) by an energy modulator **70**.

Like the area modulator **59** shown in FIG. 2, the energy modulator **70** also includes shutter pairs **51** providing corresponding modulation elements. Each shutter pair **51** may again include opposed, longitudinally extending shutters **50a** and **50b** that may be moved toward and away from each other by actuators **56**. In this case, however, each shutter **50a** and **50b** is comprised of a number of independently movable blades **74** that overlap along the direction of axis **21**. The actuators **56** may independently move each of the blades **74** of shutters **50a** and **50b**.

As before, multiple shutter elements **51** are arranged latitudinally adjacent to fill the cross-sectional area **43** of the collimated area beam **40**. As before, each shutter pair **51** may create an aperture independently controlling one latitudinal beamlet **24** (not shown in FIG. 5).

Referring now to FIG. 6, in one embodiment, the blades **74** of each shutter **50a** and **50b** may be of equal width along the axis **21**, and each blade **74** sized to attenuate the energy in, but

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not wholly block, the protons of the area beam **40**. The blades **74** may be staggered with respect to their overlap along axis **21** to create a thickness through which the area beam **40** must pass that vary longitudinally in the manner of an energy controlling compensator.

When using a distal edge tracking treatment plan, such as that described in U.S. Pat. No. 5,668,371, issued Sep. 16, 1997, assigned to the assignee of the present invention, and hereby incorporated by reference, it may be desired to place the distal edge of the Bragg peaks of the area beam **40** along a convex dose limit **76** within first region **78** of the tumor **80** having a convex distal edge. This convex dose limit **76** is implemented by causing the blades **74** to overlap so that they provide greater total material at the edges of the beamlet **24** than the center of the beamlet **24**. The exact amount of curvature may be controlled by controlling the exact amounts of overlap of the blades **74**, while only a convex dose limit **76** may be created with these blades and **74**. As can be seen by referring to both FIGS. 6 and 7, a tumor **80** with an arbitrarily complex shape may be treated by dividing the tumor **80** into several regions **78** and **82** each of which is independently convex. The blades **74** may then be shifted to provide separate treatment of each region **78** and **82** in a piecewise fashion. The treatment of first region **78** is shown in FIG. 6 and the treatment of second region **82** is shown in FIG. 7.

The particular shape of the convex dose limit **76** is controlled by computer **25** controlling the actuators **56**.

Referring now to FIG. 8, alternatively the shutter elements **51** may employ blades **74'** having different widths or effective widths (e.g., different attenuation) such that their individual attentions stand, for example, in a base-2 power sequence. In this case, each blade **74** starting at the least attenuating blade **74** may attenuate twice as strongly as the previous blade **74** with which it may overlap. In this way, the minimum number of blades **74** can be used to create the maximum number of energy steps in the beamlet **24**. A pair of opposed shutters **50a** and **50b** each having multiple blades **74** may be used, or, as shown, a single shutter **50a** of energy attenuating blades **74** may be used together with two shutters **50a** and **50b** of ion blocking blades **74''** used for intensity modulation.

The use of the binary weighted blades **74** does not allow an intuitive generation of a compensator per the approach of FIGS. 6 and 7 but allows complete control of the energy of the beamlet **24** that may be scanned as described generally in the embodiment of FIG. 2 to create an arbitrary convex dose limit **76** in a tumor **80**. In the embodiment shown in FIG. 8, the scanning is conducted by simultaneous movement of a single set of blades **74** within a beamlet **24** defined by ion-opaque blades **74** of shutters **50a** and **50b** of an area modulator **59** optionally positioned as shown in FIG. 5.

Referring now to FIG. 9, the ability of the present invention to control the intensity of the area beam **40** at different longitudinal and latitudinal positions allows the invention to correct for an irregular intensity profile **90** of the area beam **40** by action of the shutter pairs **51**. In one such implementation, the shutter system of FIGS. 6 and 7 may be used to control both intensity and energy by selecting energy attenuating blades **74** that fully block the area beam **40** when all blades **74** overlap.

In this technique, the intensity profile **90** is measured and divided into longitudinal bands **92** where the intensity may be approximated as uniform. The width of the bands **92** is determined by the amount of intensity variation that can be tolerated.

For each band **92**, its latitudinal extent is used to define a treatment region **94**, the different treatment regions **94** separately treated in sequence. Per this technique, at a first time **96**,

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the blades **74** of each of shutters **50a** and **50b** are closed against each other to fully block the area beam **40**. The interface between the blades **74** may be aligned with the center of the first treatment region **94**.

At a second time **100**, the blades **74** are retracted about the center line to create a desired compensator shape assuming a uniform intensity of the area beam within the region **94** equal to its average intensity within the band **92**.

At a next time **102**, the blades **74** are closed against each other again to fully block the area beam **40**. Their interface may then be aligned with a second band **92** and this process repeated. The amount of time between time **96** and **102** controls the intensity of radiation within the treatment region **94**, whereas the staggering of the blades **74** during time **100** controls the energy distribution and thus the depth profile of the protons.

Referring again to FIG. 1, the improved treatment speed of the present invention and elimination of the need for multiple custom compensators allows multiple angles of treatment to be obtained by rotating the gantry **12** to different positions within the orbit **16** and applying the radiation as modulated by the present invention at each position. The orbit **16** is a relative orbit with respect to the patient and, of course, may in fact be implemented by rotation of the patient in certain circumstances. In that case the gantry should be understood to be any system for making relative rotations between the patient and the beam.

It is specifically intended that the present invention not be limited to the embodiments and illustrations contained herein and the claims should be understood to include modified forms of those embodiments including portions of the embodiments and combinations of elements of different embodiments as come within the scope of the following claims.

We claim:

1. A method of modulating at least one of the intensity and range of ions comprising:

(a) generating an area beam of ions directed along an axis and having a longitudinal and latitudinal extent in cross-section;

(b) controllably occluding an area of beam with a set of longitudinally opposed latitudinally adjacent shutter pairs, each shutter of the pair controllably extended to different longitudinal distances simultaneously to control multiple discrete ion beams at different adjacent latitudinal positions and control independent longitudinal positions such that at least one of an intensity and energy of the ion beams may be independently controlled among ion beams;

whereby parallel multiple beam treatment over an area may be obtained.

2. The method of claim 1 wherein each shutter pair comprises opposed shutters each sized to fully block the ion beam from passing through the shutter and wherein the shutter pair is controlled to control a dwell time of an aperture formed between the shutters to control the intensity of the ion beam at a variety of longitudinal locations.

3. The method of claim 2 wherein the shutters of the shutter pairs are controlled both to control a center of an aperture created between the shutter pairs and a longitudinal separation between the shutter pairs whereby the longitudinal dimension of the ion beams may be controlled independently from their longitudinal position.

4. The method of claim 1 wherein each shutter comprises multiple blades each sized to only partially attenuate the energy of the ion beam passing through the blade and wherein multiple blades are independently controlled to control an

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amount of overlap among the blades and a longitudinal location of the overlap to control the energy of the ion beam at a variety of longitudinal locations.

5. The method of claim 4 wherein the multiple blades of each shutter pair when fully overlapping along an axis of the ion beam block passage of the ion beam and wherein the multiple blades of each shutter pair are further controlled to control a dwell time of an aperture formed between the multiple blades to control the intensity of the ion beam at a variety of longitudinal locations.

6. The method of claim 5 wherein the area beam has a non-uniform intensity distribution and the dwell time is controlled according to the non-uniform intensity distribution and a desired treatment intensity to correct for the non-uniform intensity distribution.

7. The method of claim 4 further including the step of: (c) controllably occluding an area of the beam with a second set of longitudinally opposed latitudinally adjacent shutter pairs, the shutters of each shutter pair sized to fully block the ion beam from passing through a shutter of the shutter pair, each shutter of the shutter pair controllably extended to different longitudinal distances to control a dwell time of an aperture formed between the shutters to control the intensity of the ion beam at a variety of longitudinal locations.

8. The method of claim 4 wherein the multiple blades when fully overlapping completely block the ion beam from passing through the blades and wherein the blades are controlled in a first state to have selective overlap to control energy and in a second state to fully block the ion beam to control intensity through dwell time adjustment.

9. The method of claim 4 wherein the blades of each shutter pair have equal thickness.

10. The method of claim 4 wherein the blades of each shutter pair have different thicknesses according to a binary sequence.

11. The method of claim 4 wherein the multiple shutters are arranged to provide a treatment surface defined by Bragg peaks of the ion beam at different longitudinal locations and including the step of dividing a treatment area up into multiple, longitudinal surfaces for sequential treatment of each surface.

12. The method of claim 1 wherein the area beam is a proton beam.

13. The method of claim 1 including the step of rotating an axis of the area beam about a patient to provide treatment of the patient at a plurality of angles.

14. An area modulator for an area beam of ions directed along an axis and having a longitudinal and latitudinal extent in cross-section, the modulator comprising:

a set of longitudinally opposed latitudinally adjacent shutter pairs; and

an actuator system controllably extending the shutters to different longitudinal distances simultaneously to control multiple discrete ion beams at different, adjacent latitudinal positions and controllable independent longitudinal positions such that at least one of an intensity and energy of the ion beams may be independently controlled among different ion beams;

whereby parallel multiple beam treatment over an area may be obtained.

15. The modulator of claim 14 wherein each shutter pair comprises opposed shutters each sized to fully block the ion beam from passing through the shutter and wherein the actuator system controls a dwell time of an aperture formed between the shutters to control the intensity of the ion beam at a variety of longitudinal locations.

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16. The modulator of claim 15 wherein the actuator system controls the shutters of the shutter pairs to control a center of an aperture created between the shutter pairs and a longitudinal separation between the shutter pairs whereby the longitudinal dimension of the ion beams may be controlled independently from their longitudinal position.

17. The modulator of claim 14 wherein each shutter comprises multiple blades each sized to only partially attenuate the energy of the ion beam passing through the blade and wherein the actuator system independently controls the multiple blades to control an amount of overlap among the blades and a longitudinal location of the overlap to control the energy of the ion beam at a variety of longitudinal locations.

18. The modulator of claim 15 wherein the multiple blades of each shutter pair when fully overlapping along an axis of the ion beam block passage of the ion beam and wherein the actuator system controls the multiple blades of each shutter pair to control a dwell time of an aperture formed between the multiple blades to control the intensity of the ion beam at a variety of longitudinal locations.

19. The modulator of claim 17 further including a second set of longitudinally opposed latitudinally adjacent shutter pairs, the shutters of each shutter pair sized to fully block the ion beam from passing through the shutter, wherein the actuator system controls each shutter of the pair to different longitudinal distances to control a dwell time of an aperture formed between the shutters to control the intensity of the ion beam at a variety of longitudinal locations.

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20. The modulator of claim 17 wherein the multiple blades when fully overlapping completely block the ion beam from passing through the blades and wherein the actuator system controls the blades in a first state to have selective overlap to control energy and in a second state to fully block the ion beam to control intensity through dwell time adjustment.

21. The modulator of claim 17 wherein the blades of each shutter pair have equal thickness.

22. The modulator of claim 17 wherein the blades of each shutter pair have different thicknesses according to a binary sequence.

23. The modulator of claim 15 wherein the area beam has a non-uniform intensity distribution and the actuator system controls dwell time according to the non-uniform intensity distribution and a desired treatment intensity to correct for the non-uniform intensity distribution.

24. The modulator of claim 17 wherein the multiple shutters are arranged to provide a treatment surface defined by Bragg peaks of the ion beam at different longitudinal locations and the actuator system controls the shutters to provide sequential treatment of multiple, longitudinal surfaces a tumor.

25. The modulator of claim 14 including a gantry for rotating the modulator about a patient to provide treatment of the patient at a plurality of angles.

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