NOVEL APPROACH TO UTILIZE PROTON BEAMS FROM HIGH POWER LASER ACCELERATORS FOR THERAPY

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Abstract

Protons provide superior radiotherapy benefits to patients, but immense size and cost of the system limits it to only few centers worldwide. Proton acceleration on µm scale via high intensity laser is promising to reduce size and costs of proton therapy, but associated beamlines are still big and massive. Also, in contrast to conventionally accelerated quasi-continuous mono-energetic pencil beams, laser-driven beams have distinct beam properties, i.e. ultra-intense pico-sec bunches with large energy spread and large divergences, and with low repetition rate. With new lasers with petawatt power, protons with therapy related energies could be achieved, however, the beam properties make it challenging to adapt them directly for medical applications. We will present our compact beamline solution including energy selection and divergence control, and a new beam scanning and dose delivery system with specialized 3D treatment planning system for laser-driven proton beams. The beamline is based on high field iron-less pulsed magnets and about three times smaller than the conventional systems, and can provide high quality clinical treatment plans.

INTRODUCTION

The rapid advancement in laser-driven proton acceleration has made Laser-based Proton Therapy (L-PT) an attractive alternative to the existing Proton Therapy (PT) facilities, in terms of size and cost reduction [1-3]. In laser-driven acceleration, an ultra-intense laser pulse interacts with thin targets and accelerates intense proton bunches on µm scale. However, in contrast to narrow mono-energetic beams from conventional accelerators, laser-driven beams are characterized by short pulses of high particle flux, low pulse repetition rate (≤ 10 Hz), broad energy spectrum (up to 100%), large divergence (≥ 10°) and large pulse-to-pulse fluctuation. In addition to laser particle accelerator development for generating therapeutically applicable proton beams, the distinct features of these beams demand new beam transport and dose delivery system designs. Moreover, a specialized 3D treatment planning system (TPS) would be needed to make treatment plans with pulsed proton bunches with large energy widths and is able to optimize required number of laser pulses for good clinical plans. The conventional solutions cannot be applied directly to L-PT and new approaches are needed for beam transport and also for the dose delivery to efficiently deliver treatment plans [4, 5].

MATERIALS AND METHODS

The intrinsic distinct features of laser-driven beams require a transport beam-line with multiple functions all integrated in a rotating gantry system for achieving a more compact system. Also, the pulsed nature of laser system and laser-driven beams allowed us to consider pulse powered air-core magnets for the gantry design. Unlike conventional iron-core magnets, pulsed magnets are not limited by iron's saturation of magnetization to 2 T and provide higher magnetic fields (e.g. up to 10 T dipole fields) which can bend high energy protons in smaller radius and hence more compact designs are achievable. We present our compact pulsed gantry design for laser-driven protons and two novel field formation techniques. The main features of the improved design are given below.

Firstly, a two-step capturing system is introduced, behind the laser-target, for proton initial divergence control for maximum efficiency. Secondly, an energy selection system (ESS) is included which is necessary for filtering initially available energy spectrum for ensuring precise and conform dose delivery for individual patients. To deliver doses to tumor volumes a certain range of proton energy is needed, this energy window is already available in the initial spectrum. For utilizing intense laser-driven proton bunches efficiently, the ESS is required to filter large selectable energy widths, say $\Delta E/E_0$ ~ 2-20 % in fixed steps. A beamline is required to be designed capable to transport filtered large energy widths in a gantry for-

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mation, so that the beam can be rotated around the patient for flexible multi-field irradiations.

Thirdly, the novel function of this gantry is to deliver the protons in specified field formations to implement 3D intensity modulated treatment plans. Conventionally, two methods are being deployed 1) Passive field formation via physically broadening the mono-energetic pencil beam by the use of scatterers and then shaping it downstream with collimators to cover the tumor area, also, range modulation is then utilized to conform the beam to the tumor shape in depth. 2) Active scanning of a mono-energetic pencil beam via magnetic fields for irradiation of the tumor area. In this scheme, generally, the beam is scanned in spots laterally covering one tumor slice in depth and then by changing the beam energy the full depth of the tumor is scanned.

For laser-driven proton beams with about 20x larger energy spread and about 10x the size compared with conventional beams, new field formation techniques are required. We have designed two methods:

1) Magnetic beam broadening for large field irradiation akin to passive field formation by scatterer. A set of three quadrupoles is used to focus or defocus the beam to a spot size required at iso-center. This changes the proton flux within the irradiation field and prevents the unnecessary particle loss in the collimators.

2) Short-throw magnetic scanning for precise spot/sub-volume irradiation, via dipole field formed by placing two solenoids facing each other with beam traversing in perpendicular direction.

In order to investigate the dose delivery by such a gantry system and the quality of treatment plans achievable by intense pulsed laser-driven proton beams, a dedicated 3D TPS has been developed which is based on the open source TPS CERR (A Computational Environment for Radiation Research) [4]. This 3D TPS is capable to calculate 3D dose distributions on real patient data by utilizing beams with broad energy spectra and optimizing parameters, like proton number per bunch and energy distribution. This optimization maximizes the proton use per bunch and to minimize the delivery time for one plan compared to a irradiation with nearly mono-energetic beams, as the crucial limitation is the treatment delivery time via 10 Hz laser systems. The development of the 3D TPS was presented last year. This year we will present some important results of the feasibility study performed on the basis of evaluating treatment plans on clinical parameters like tumor coverage and dose conformity.

RESULTS

The gantry design is characterized by capturing and focusing the divergent laser-driven proton beam by two solenoid lenses, the capture efficiency up to 99% has been simulated. The capturing is followed by an ESS which is based on a 90° bending magnet in combination with quadrupole lenses. Energy bands in range of $\Delta E/E_0 \sim$ 2-20 % in 1% steps could be filtered as a function of the radius of the ESS aperture. A gantry transport beamline was designed and simulated to transport such large beams, in energy and size. The dose delivery and field formation techniques have been simulated. For magnetic beam broadening, beam spot sizes of 2 - 20 cm in diameter could be achieved via selectable strengths of the quadrupole triplet. For magnetic scanning, beams with as large as 5 cm spot sizes and 20% energy widths could be scanned in both x- and y- direction for 20×20 cm^2 field sizes. The optimized design with pulsed magnets has resulted in a compact gantry with size of 5 m in diameter and 3 m in length. The integrated high resolution and high acceptance energy selection and beam transport system has resulted in transport efficiencies of up to 90%.

Multiple 3D treatment plans were calculated with varied beam properties and were then evaluated on clinical parameters, like dose conformity and tumor. It could be shown that clinically relevant plans were achievable with pulsed laser-driven proton sources (10 Hz) with treatment times ranging from 16 to 6 minutes. The higher treatment times required about 9600 laser pulses per fraction of 2 Gy, with about 10^7 proton per bunch, and we could see (even up to 30%) pulse-to-pulse fluctuation in laser shots does not have significant effect on the dose volume histogram of the target volume or the evaluated parameters. However, for the same tumor volumes, the treatment plans which would require about 4000 laser pulses, with about 10^9 protons per bunch, showed significant pulse-to-pulse fluctuation effect on plan quality. The result of this feasibility study also provides feedback to laser community, such as importance of robust and less expensive laser-targets and the requirement to laser acceleration stability window for given number of protons per bunch.

SUMMARY

Our improved gantry based on pulsed magnets would provide a compact system for proton beam therapy with laser-driven sources and we have presented novel ideas for beam scanning with wide beams for efficient tumor irradiations. The development, including design, realization and tests, of pulsed magnetic elements for the gantry are being carried on. Whereas, the TPS feasibility has provided us with limitations and clinical requirements important for further developments in both gantry systems and laser-acceleration fields.

OUTLOOK

For future L-PT development, the conventional proton therapy facility at OncoRay, Dresden is additionally equipped with a high-intensity laser laboratory and an experimental irradiation bunker. This will provide testing facility for clinical applicability of laser-based systems side-by-side with the conventional therapeutic proton beams as reference.

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