Assessment of secondary radiation and radiation protection in laser-driven proton therapy

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Abstract

This work is a feasibility study of a radiation treatment unit with laser-driven protons based on a state-of-the-art energy selection system employing four dipole magnets in a compact shielded beamline. The secondary radiation emitted from the beamline and its energy selection system and the resulting effective dose to the patient are assessed. Further, it is evaluated whether or not such a compact system could be operated in a conventional treatment vault for clinical linear accelerators under the constraint of not exceeding the effective dose limit of 1 mSv per year to the general public outside the treatment room. The Monte Carlo code Geant4 is employed to simulate the secondary radiation generated while irradiating a hypothetical tumor. The secondary radiation inevitably generated inside the patient is taken into account as well, serving as a lower limit. The results show that the secondary radiation emanating from the shielded compact therapy system would pose a serious secondary dose contamination to the patient. This is due to the broad energy spectrum and in particular the angular distribution of the laser-driven protons, which make the investigated beamline together with the employed energy selection system quite inefficient. The secondary radiation also cannot be sufficiently absorbed in a conventional linear accelerator treatment vault to enable a clinical operation. A promising result, however, is the fact that the secondary radiation generated in the patient alone could be very well shielded by a regular treatment vault, allowing the application of more than 100 fractions

Untersuchung zur Sekundärstrahlung und zum Strahlenschutz bei der Strahlentherapie mit Laser-beschleunigten Protonen

Zusammenfassung

Diese Arbeit ist eine Machbarkeitsstudie für ein Strahlentherapiesystem mit Laser-beschleunigten Protonen, das auf dem aktuell diskutierten Energieselektionssystem mit vier Dipolmagneten in einem kompakten, abgeschirmten Strahlführungssystem basiert. Die von der Strahlführung und dem Energieselektionssystem emittierte Sekundärstrahlung und die resultierende effektive Dosis des Patienten werden ausgewertet. Weiterhin wird untersucht, ob ein solches kompaktes System in einem konventionellen Bestrahlungsbunker für klinische Linearbeschleuniger betrieben werden könnte, ohne dass die effektive Dosis für die Öffentlichkeit außerhalb des Bestrahlungsraumes 1 mSv pro Jahr überschreitet. Der Monte-Carlo-Code Geant4 wurde verwendet, um die entstehende Sekundärstrahlung während der Bestrahlung eines hypothetischen Tumors zu simulieren. Die unausweichlich im Patienten selbst generierte Sekundärstrahlung wird ebenfalls berücksichtigt und dient als untere Grenze. Die Resultate zeigen, dass die Sekundärstrahlung, die das abgeschirmte kompakte Bestrahlungssystem verlässt, eine ernsthafte Belastung des Patienten mit Sekundärdosis darstellen würde. Die Gründe dafür sind das breite

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of 2 Gy per day with protons. It is thus theoretically possible to treat patients with protons in such treatment vaults. Nevertheless, the results show that there is a clear need for alternative more efficient energy selection solutions for laser-driven protons.

Keywords: Monte Carlo, laser-driven protons, proton therapy, secondary radiation

Energiespektrum und insbesondere die Winkelverteilung der Laser-beschleunigten Protonen, die das untersuchte Strahlführungssystem zusammen mit dem verwendeten Energieselektionssystem sehr ineffizient machen. Die Sekundärstrahlung kann auch von einem konventionellen Bestrahlungsbunker für Linearbeschleuniger nicht ausreichend abgeschirmt werden, um einen klinischen Betrieb zu ermöglichen. Ein vielversprechendes Resultat hingegen ist die Tatsache, dass die nur im Patienten erzeugte Sekundärstrahlung sehr wohl von einem normalen Bestrahlungsbunker abgeschirmt werden kann. Ein konventioneller Bestrahlungsraum würde es erlauben, über 100 Fraktionen zu je 2 Gy pro Tag mit Protonen zu applizieren. Es ist daher theoretisch möglich in solchen Bestrahlungsräumen Patienten mit Protonen zu behandeln. Allerdings zeigen die Resultate eindeutig, dass alternative, effizientere Ansätze zur Energieselektion von Laser-beschleunigten Protonen notwendig sind.

Schlüsselwörter: Monte Carlo, Laserbeschleunigung, Protonentherapie, Sekundärstrahlung

1 Introduction

Protons are renowned in radiation therapy for their ability to place dose in a tumor volume very precisely due to the characteristic Bragg peak. It is therefore desirable to have compact devices for proton therapy at hand that are easily available. So far, proton therapy is only performed in dedicated facilities using a cyclotron or synchrotron for proton acceleration and enormous particle gantries for their application to the patient. Protons can be accelerated with lasers as well, making it theoretically possible to build compact single room systems since the protons are accelerated over a very short distance and the laser light can be deflected around the patient in a gantry requiring much less space than the magnets necessary to deflect a proton beam [1]. In contrast to conventionally accelerated protons, laser-driven protons typically exhibit a broad energy spectrum, making it possible to select the protons with the desired energy, but at the same time this requires a solution for energy selection and the stopping of protons with unwanted energy which will inevitably produce a lot of secondary particles. Also, experimental results with laser-driven protons have not yet reached energies that are high enough for clinical applications.

The work presented here is a feasibility study of a hypothetical compact laser-driven proton therapy system (based on the current knowledge about laser-driven particle acceleration) regarding the dose delivered to the patient by secondary particles and with regard to radiation protection considerations if such a system is operated in a conventional (existing) treatment room designed for clinical electron linear accelerators (linacs) for therapeutic electron and photon beams. This study is based on simulations using the Monte Carlo code Geant4 [2,3]. The central question posed here is whether or not such a hypothetical compact device could be operated in a standard linac room as replacement of an existing linac. Such a compact therapy system operated with laser-driven protons and without the need of building a new treatment vault might be considerably cheaper than a conventional dedicated proton therapy facility, therefore possibly making proton therapy available to much more patients.

The energy selection technique applied here uses four dipole magnets and is based on the work of Fourkal et al. [4] (see Fig. 1 for an outline of the corresponding beamline). Such systems have been realized experimentally [5,6] and are frequently referred to in the relevant literature. This concept may therefore still be considered the current state of research, although doubts about its applicability for clinical use are pertinent (e.g. regarding the efficiency of the system, cf. [7]) and novel concepts are being developed to overcome this limitation [8]. The assumed initial energy spectrum of the protons used here is very broad (with energies up to 300 MeV) and derived by extrapolating current experimental spectra to higher energies (as done in [9] and [8]). This is based on the target normal sheath acceleration (TNSA) mechanism [10] or other acceleration regimes that show broad energy spectra (e.g. [11]). Energies of 300 MeV have not yet been experimentally shown (the current record is about 160 MeV [12]), but are a prerequisite for clinical applications (required energy range for proton therapy: 70 MeV to 250 MeV). In our study, we will investigate in more detail whether the proposed energy selection system (with some modifications to make it more realistic) is feasible for clinical applications, with a focus on