BEAM CONDITIONING SYSTEM FOR LASER-DRIVEN HADRON THERAPY

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Abstract

While the superior therapeutic efficacy of hadron therapy has been clearly demonstrated, its availability to cancer patients is limited by the cost and size of current systems. RadiaBeam Technologies, in collaboration with the UCLA Department of Radiation Oncology and the University of Texas at Austin, is proposing the utilization of innovative laser-driven ion acceleration (LDIA) technology for the development of a compact, inexpensive proton therapy system that can ultimately be adapted for the acceleration of carbon ions. At less than a third the price of the average proton therapy unit, the realization of this system would make hadron therapy a much more realistic option for hospitals and clinics worldwide. However, LDIA produces a beam with large divergence, wide energy spread with multiple ion species, and a significant background of electrons and X-rays. Thus, a major challenge for clinical implementation of LDIA is the development of a post-target beam conditioning system for collimation, focusing, energy selection, background shielding, and scanning. This paper will discuss the progress of our design of such a system and plans for future testing.

INTRODUCTION

Around 4% of people in developed countries are diagnosed with cancer each year and more than 50% of these patients receive some form of radiation treatment, making radiotherapy the most common as well as the most successful form of cancer therapy [1]. Although most radiotherapy is currently performed with photons, proton therapy is quickly gaining popularity for its ability to target tumors with higher doses and less damage to healthy surrounding tissue than is possible with electron or photon therapy. However, patient access to proton treatment is extremely restricted due to its high costs and limited availability. Though carbon ions may be an even better treatment option for most patients, as they have less spatial scattering and higher relative biological effectiveness [2], carbon therapy systems are even more costly – over $200 million [3].

RadiaBeam Technologies, UCLA, and the University of Texas at Austin (UTA) are proposing to address this problem by using innovative laser-driven ion acceleration (LDIA) techniques to demonstrate high-energy protons and design a significantly more compact, less expensive proton therapy system. One major advantage of this technology is the ability to transition relatively easily from the acceleration of protons to carbon ions in future stages of development. The utilization of this cost-saving (as well as space-saving) accelerator technology for carbon ion therapy would be groundbreaking for the future of cancer treatment.

ACCELERATION MECHANISMS

The first task of this project is to demonstrate beam parameters from the LDIA source, which will be done at UTA using the Petawatt Laser facility. Recent developments in LDIA that show promise to extend the energy range and increase the efficiency of the acceleration process have taken advantage of the so-called transparent overdense regime [4]. The transition to this regime occurs when the target is thin enough, and the laser intensity and contrast high enough, for all of the target electrons to be removed from the material at once. This relativistically transparent target allows the laser field to interact with the entire target while it is still overdense, and the entire ion population can be accelerated in unison using an acceleration mechanism dubbed "Break-Out Afterburner" (BOA) acceleration. This mechanism has been explored extensively over the last three years at Los Alamos National Laboratory both experimentally and in simulations (as shown in Figure 1) [5]. Another advanced LDIA mechanism under investigation is Radiation Pressure Acceleration (RPA), which is capable of producing a more mono-energetic ion energy spectrum.

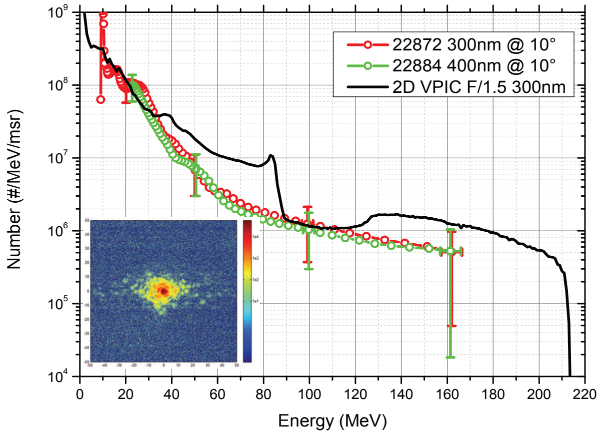

Figure 1: Proton spectra from interaction of LANL trident laser with 80 J, 600 fs, r < 2 μm with 300 nm and 400 nm CH_2 targets. Inset shows focal spot with F/1.5 off-axis parabola [6].

ENERGY SELECTION AND BEAM COLLIMATION

Proton beams produced through LDIA will have large divergence and wide bandwidths, necessitating an

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efficient system for focusing, collimating, and narrowing the energy spread, as well as directing the beam to the precise tumor location. Conventional accelerators use heavy collimators and bending magnets to meet these needs, sacrificing system cost and size for beam quality. In order to successfully exploit these novel acceleration mechanisms for proton therapy, it is crucial to develop a compact, high-performance conditioning system that takes advantage of the small source size from LDIA.

This can be achieved through the use of permanent magnet quadrupoles (PMQs), with which RadiaBeam has extensive fabrication and testing experience (see Fig. 2). PMQs have the advantage of allowing very small magnet geometries with high peak fields, which allow high gradients for focusing charged particle beams.

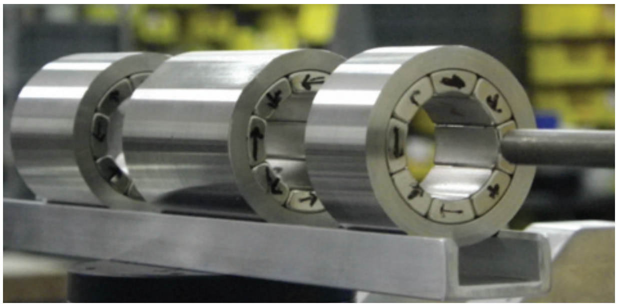

Figure 2: PMQ triplet at RadiaBeam test stand [7]. This design was recently successfully tested at ATF BNL, where a 300 pC, 70 MeV electron beam was focused to a 6 µm RMS spot size [8].

Initial simulations were performed with the elegant particle tracking code [9] to determine the feasibility of such a focusing scheme. An adapted collider final focus system with a PMQ triplet was used for simulation, with beam characteristics consistent with previously published data for laser-driven protons. The resulting energy spread is shown in Fig. 3, with the distribution before energy selection shown in black and after shown in red.

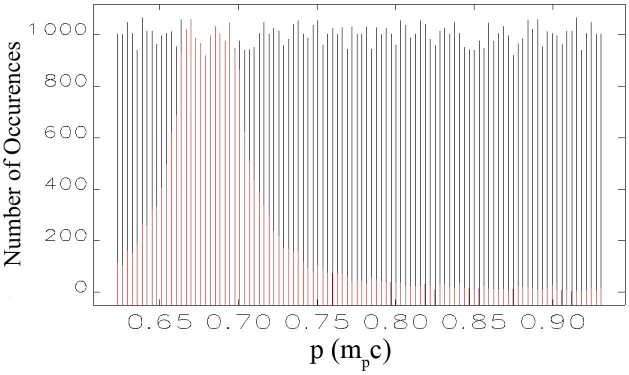

Figure 3: Energy spread of laser-driven protons before (in black) and after (in red) collimation with an adapted collider final focus system with PMQ triplet, simulated in elegant.

Although this simulation shows reasonably good energy selection, the resulting beam size with this focusing setup is still too large to be practical for proton therapy. Also, due to the extremely large divergence of laser-driven beams, about 25% of the charge was collected in this collimation scheme.

These are preliminary simulations with a relatively simple PMQ and collimator setup. We are currently exploring more optimized focusing schemes that should be able to collect a larger portion of the original beam and focus down to much more realistic spot sizes for a pencil beam scanning therapy system. One alternative is the utilization of two PMQ doublets rather than a triplet, but further simulations must be performed to determine the feasibility and optimal geometry of such a system.

SHIELDING

To prevent destruction from radiation and debris, including unwanted neutrons, photons, or electrons produced by the laser, shielding layers must be incorporated in front of each of the PMQs. The entire post-target conditioning system must also have sufficient shielding to limit the radiation exposure to the level recommended by the National Council on Radiation Protection and Measurement (NCRP). The leakage radiation one meter from the source must not exceed 0.1% of the primary beam at its isocenter.

Due to the especially large number of these unwanted particles produced through the proposed LDIA techniques and the need to keep the system compact and lightweight, this incorporated shielding scheme must be relatively complex. The shielding of the primary collimator, in front of each PMQ, and around the entire conditioning system should be a combination of steel, tungsten, polyethylene, and lead to shield from protons, high-energy neutrons, low-energy neutrons, and photons and gamma rays, respectively [10]. This shielding design will be optimized to keep the entire conditioning system as compact and lightweight as possible while minimizing radiation exposure and damage to the PMQs.

CONCLUSION

The LDIA technology to be developed in this project would enable the production of protons and carbon ions of unparalleled energy and quality in a fraction of the length needed with a conventional design. These beams require a powerful post-target conditioning system for focusing and collimating the beam, as well as narrowing its energy spread. RadiaBeam is designing such a system by taking advantage of the compact geometries and high gradients achievable with PMQs. This presents various challenges, such as the high divergence of the laser-driven ion beam and small PMQ aperture necessary for focusing high-energy (~250 MeV) protons, which RadiaBeam is currently working to overcome.

This compact acceleration technology and conditioning scheme would allow the entire treatment system to become significantly smaller and less expensive, making it a much more realistic option for treatment centers worldwide. In addition to widening the global availability of proton/carbon therapy, this major decrease in the price of the system would further expand the pool of potential patients by greatly reducing the cost per treatment. As proton treatment is shown to have a five-year survival rate equal to that of patients treated with surgery, as well as fewer side effects than those treated with X-ray therapy, the widespread development of affordable proton therapy centers could improve both cancer survival rates and the quality of life for all cancer patients.

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