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A Compact Linac for Proton Therapy Based on a Dielectric Wall Accelerator*

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Abstract

A novel compact CT-guided intensity modulated proton radiotherapy (IMPT) system is described. The system is being designed to deliver fast IMPT so that larger target volumes and motion management can be accomplished. The system will be ideal for large and complex target volumes in young patients.

The basis of the design is the dielectric wall accelerator (DWA) system being developed at the Lawrence Livermore National Laboratory (LLNL). The DWA uses fast switched high voltage transmission lines to generate pulsed electric fields on the inside of a high gradient insulating (HGI) acceleration tube. High electric field gradients are achieved by the use of alternating insulators and conductors and short pulse times. The system will produce individual pulses that can be varied in intensity, energy and spot width. The IMPT planning system will optimize delivery characteristics. The system will be capable of being sited in a conventional linac vault and provide intensity modulated rotational therapy.

Feasibility tests of an optimization system for selecting the position, energy, intensity and spot size for a collection of spots comprising the treatment are underway. A prototype is being designed and concept designs of the envelope and environmental needs of the unit are beginning. The status of the developmental new technologies that make the compact system possible will be reviewed. These include, high gradient vacuum insulators, solid dielectric materials, SiC photoconductive switches and compact proton sources.

Conflict of Interest: Some of the authors have financial interest in TomoTherapy, Inc., which has licensed the DWA technology from LLNL.

KEYWORDS: Hadron therapy, proton therapy.

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1. Introduction

A new type of accelerator is under development at the Lawrence Livermore National Laboratory. It combines a number of new technologies and was originally intended to provide a new generation of compact, high current accelerators for flash x-ray radiography. The Dielectric Wall Accelerator (DWA) employs a novel vacuum insulator capable of withstanding high electric fields across its surface for short times (on the order of tens of ns) [1]. There is a general inverse dependence of the surface breakdown field stress with pulsewidth. In principle this trend could be exploited to achieve a high accelerating gradient that might be used to build a compact linac for proton therapy.

2. DWA for Flash X-ray Radiography

Very high x-ray doses are required for flash x-ray radiography. To produce these doses in a single pulse of tens of nanoseconds requires that thousands of Amperes of electrons be accelerated to energies of the order of 20 MeV. The DWA is an inherently low impedance structure and is well suited to accelerating these types of beam currents. The structure in figure 1 shows a DWA cell composed of a *high gradient insulator* that is powered by a pulse generating line that is one of a class of lines known as zero integral pulse forming lines [2].

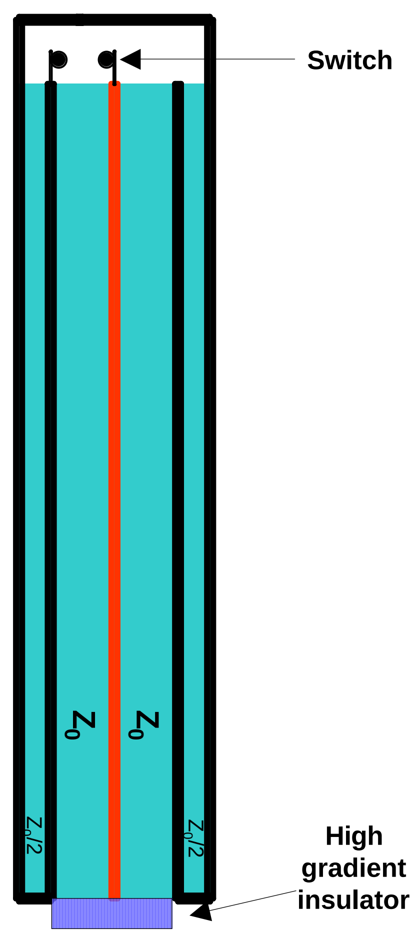

Fig. 1 - A particular zero integral pulse forming line is shown that is well suited for a compact accelerator cell. A closing switch is necessary to launch the pulse once the lines are charged. The output of the pulse forming line appears across the high gradient insulator that forms the bulk of the beam tube wall. The cells are connected together to form an accelerator.

In order for the pulse-generating line to produce a pulse a switch must close across one of the charged transmission lines.

3. Sequential Pulse Traveling Wave Concept for Proton Therapy

A new architecture is suggested by the inverse dependence of vacuum insulator breakdown strength with pulsewidth. In order to attain the largest possible accelerating gradient very short pulses must be applied to the wall. The pulses cannot be made arbitrarily short, as the on-axis gradient will fall off when compared with that at the wall. Maxwell's equations enable us to derive a constraint on the minimum acceptable pulsewidth that will preserve the on-axis gradient.

In order to provide the maximum gradient we consider the geometry shown in figure 2. It shows many charged pulse-generating lines that feed a continuous high gradient insulator vacuum wall. By timing the closing of the individual switches in the lines appropriately we may generate a region of electric field on the wall that can be made to move at any desired speed. In particular, we can arrange this speed so that the region of electric field is synchronous with a commoving, accelerating charge bunch.

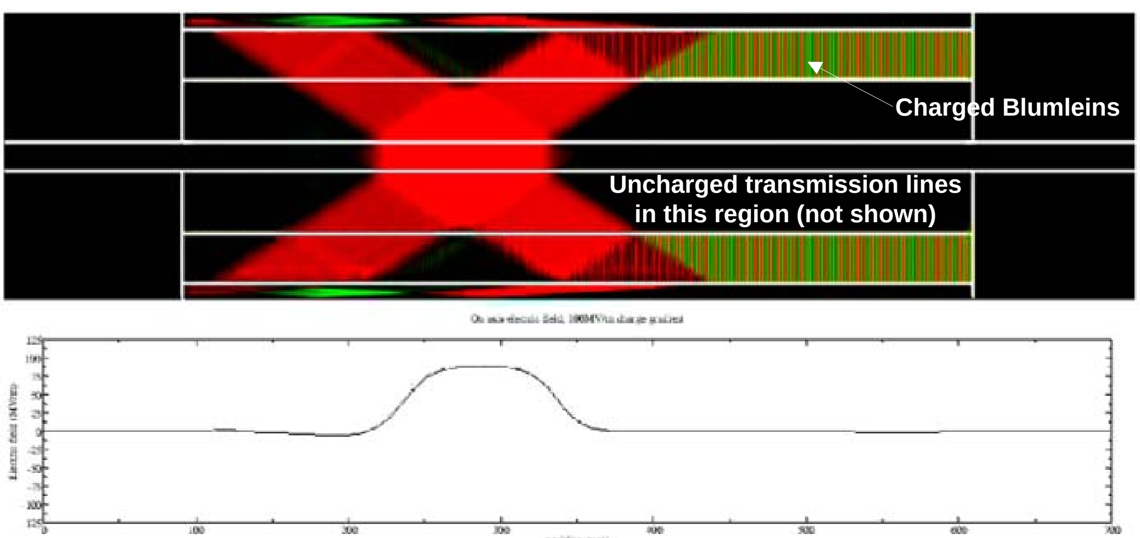

Fig. 2 – Sequential pulse traveling wave accelerator concept. The figure shows many charged pulse-generating lines, which feed a continuous, insulating beam tube. By timing the switches in each line a virtual traveling wave of electric field (red area) can be made to move along the beam line at any desired speed. The lower portion of the figure shows the on-axis longitudinal electric field as a function of axial position.

It is important to note that this is a *virtual traveling wave*, which is constantly reinforced by local excitation from each pulse-generating line in contrast to a propagating wave as in conventional waveguide accelerators.

Since the pulse-generating lines are recharged every time it is possible to change the energy of the beam from pulse to pulse.

4. Technologies for the DWA

Proton therapy requires energies in the range of 70 – 250 MeV. Our goal is to make a linac so compact that it can be installed in a conventional vault used for x-ray treatments. To do so would require an average accelerating gradient of approximately 100 MV/meter to yield a linac of order 2.5 meters in length. In order to push the accelerator performance to these levels the high gradient insulators, solid dielectrics and switches must all be capable of operating at very electric field stresses.

HGI's have achieved gradients of 100 MV/meter on small samples for pulses a few nanoseconds long [3]. Several dielectric materials used in the pulse-generating lines have demonstrated bulk breakdown strengths considerably greater than 100 MV/meter. In particular, a pulse-generating line has been demonstrated in the laboratory that produces a 5 ns output pulse with a working dielectric stress of 100 MV/meter [4].

The switching technology that is being pursued for this accelerator is a photoconductive switch fabricated from SiC. First generation switches have achieved satisfactory operation at up to 27 MV/meter average stress and an enhanced stress at the edge of the electrodes of approximately 250 MV/meter [5]. The next generation switches incorporate design features to substantially lower the enhanced fields, which limit the average working stress of the switches.

5. Treatment concept

Proton therapy requires energies in the range of 70 – 250 MeV and our goal is to fit the linac in a conventional vault used for x-ray therapy. Such a machine could be mounted on a small rotating gantry to provide rotational therapy (see figure 3).

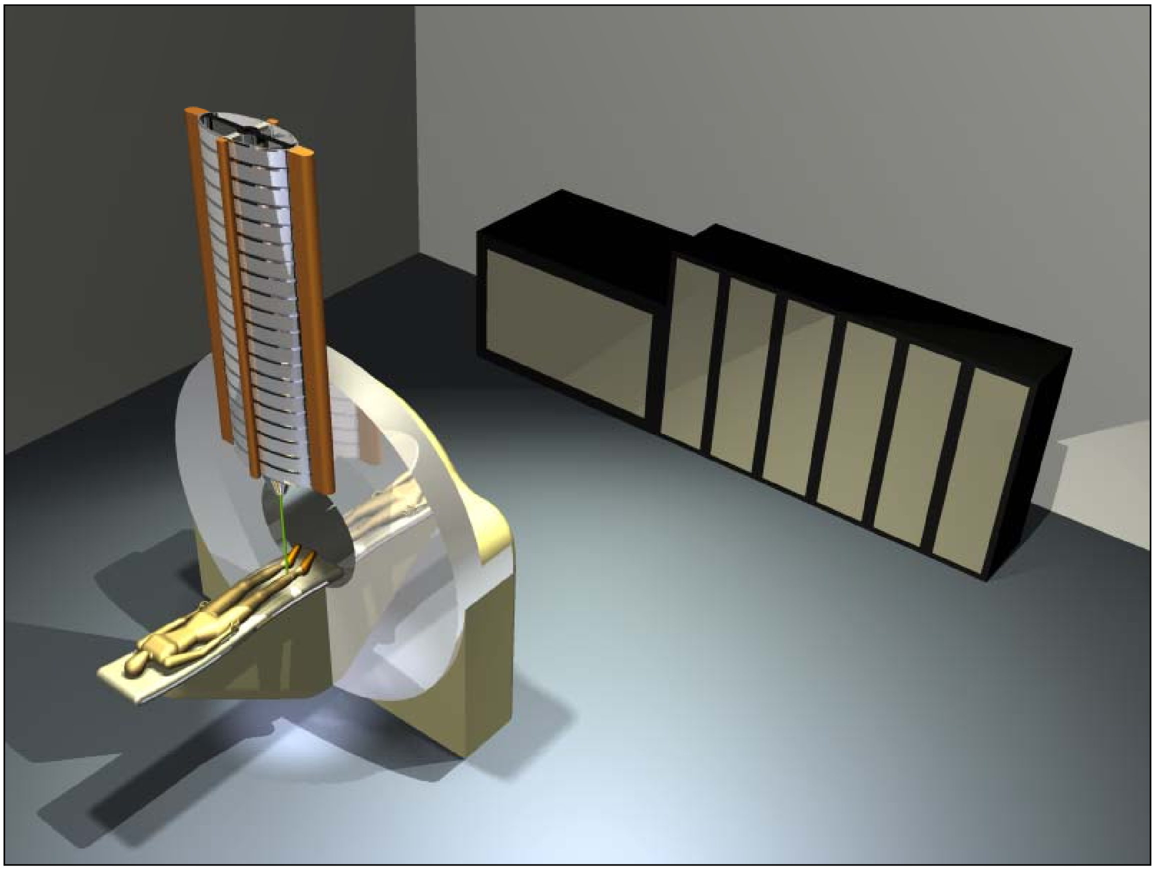

Fig. 3 – Artist's rendition of a possible proton therapy system.

Extraction of protons from the source and focusing are accomplished electrically by adjusting pulsed voltages on various electrodes. This affords the possibility of controlling the charge per bunch, spot size and beam energy on a pulse to pulse basis. We are aiming at repetition rates of many tens of Hz. Such a machine is capable of providing rotational intensity modulated proton therapy (IMPT).

6. Conclusions

A concept for a novel virtual traveling wave accelerator has been described that has the potential for 100 MV/meter operation and that would enable an IMPT accelerator mounted on a small gantry to be retrofit into a conventional linac vault.

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REFERENCES

[1] G.J. Caporaso, et. al., "High Gradient Induction Accelerator", Proceedings of the 2007 Particle Accelerator Conference, pp. 857-861.
[2] M.A. Rhodes, "Ferrite-Free Stacked Blumlein Pulse-Generator for Compact Induction Linacs, Proc. Of 2005 IEEE Pulsed Power Conf., pp. 1192-1194.
[3] W.C. Nunnally, et. al., "Investigation of Vacuum Insulator Surface Dielectric Flashover Strength with Nanosecond Pulses", Proc. 2003 IEEE Pulsed Power Conf., pp. 301-304.
[4] D.A. Sanders, et. al., "Development of a Low Loss, High Dielectric Strength Microwave Substrate", Conf. Record of 27th International Power Modulator Symposium 2006, pp. 291-294. M.A. Rhodes, et. al., "Oil-Switched Planar Blumlein Pulse Generators for Dielectric Wall Accelerators", Conf. Record of 27th International Power Modulator Symposium 2006, pp. 415-418 and subsequent improvements reported in [2].
[5] J.S. Sullivan and J.R. Stanley, "6H-SiC Photoconductive Switches Triggered at Below Bandgap Wavelengths", Conf. Record of 27th International Power Modulator Symposium 2006, pp. 215-218.