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Hospital-Based Proton Linear Accelerator for Particle Therapy and Radioisotope Production *

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Hospital-Based Proton Linear Accelerator for Particle Therapy and Radioisotope Production

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Abstract

Taking advantage of recent advances in linear accelerator technology, it is possible for a hospital to use a 70 MeV proton linac for fast neutron therapy, boron neutron capture therapy, proton therapy for ocular melanomas, and production of radiopharmaceuticals. The linac can also inject protons into a synchrotron for proton therapy of deep-seated tumors. With 180 microampere average current, a single linac can support all these applications. This paper presents a conceptual design for a medical proton linac, switchyard, treatment rooms, and isotope production rooms. Special requirements for each application are outlined and a layout for sharing beam among the applications is suggested.

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Introduction

Conventional radiation therapy for cancerous tumors is carried out using photons either from a cobalt source or from an electron linac that provides intense electron beams which produce photons by striking a tungsten target. An electron linac can also provide low-intensity electron beams for direct superficial therapy. Limitations to conventional therapy include: i) the side effects caused by damage to healthy tissue which is irradiated in the process of treating the tumor, ii) the fact that some tumors are radioresistant, that is, not controlled by conventional therapy, and iii) limitations in diagnosing and localizing tumors, particularly early-stage tumors and tumors in soft tissue. These three limitations have been addressed over the past twenty years, primarily using accelerators and equipment at physics research laboratories. Four promising avenues have emerged: (i) charged-particle beams (and particularly protons) have been used to decrease the dose to healthy tissue by using the Bragg peak to localize the dose to diseased tissue; (ii) the high relative biological effectiveness and penetrating power of fast neutrons provide local control for certain radioresistant tumors; (iii) boron neutron capture therapy (BNCT) offers hope for incurable brain tumors; (iv) advances in imaging techniques including Positron Emission Tomography (PET), which uses short-lived isotopes, are addressing the third limitation. A hospital-based facility that could take advantage of advances in all these areas would provide a great step forward in cancer treatment as well as early diagnosis of other diseases. This paper shows how a modern proton linear accelerator (linac) can be used to make such a facility possible. Section I summarizes existing methods for proton therapy, fast neutron therapy, BNCT and PET isotope production. Section II presents a scenario for providing all these techniques at a single facility.

I. Ongoing Medical Research at Physics Laboratories

A. Proton Therapy

Use of the Bragg peak to optimize dose distributions was originally suggested by Robert Wilson [1]. Clinical research at the Harvard University Cyclotron has shown that approximately 70 MeV protons can successfully treat ocular melanomas [2] and research continues on the efficacy of higher-energy protons for more deep-seated tumors. With the assistance of physicists from

Fermi National Accelerator Laboratory (Fermilab), Loma Linda University Medical Center has constructed the first hospital-based proton therapy facility in the world [3]. If clinical results are as good as expected, there will be strong demand for similar facilities. Efforts are already underway to find more cost-effective ways to provide 70-250 MeV protons for proton therapy [4].

B. Fast Neutron Therapy

Clinical fast neutron therapy at Fermilab has moved from being National Cancer Institute funded research to being the treatment of choice for certain inoperable, radioresistant tumors. For most of the patients, treatments are now covered by health insurance. The Fermilab Neutron Therapy Facility has more than fifteen years experience using 66 MeV protons from a proton linac to generate fast neutrons to treat about 1800 patients.

C. Boron Neutron Capture Therapy

This therapy is directed primarily at inoperable advanced brain tumors. Conventional radiation therapy techniques can provide temporary control, but at present they cannot provide a tumoricidal dose without causing unacceptable damage to healthy tissue. BNCT sensitizes the tumor by loading it with a boron compound and taking advantage of the high cross section for $^{10}B(n,\alpha\gamma)Li^{7}$. Epithermal neutrons (~1 keV) seem to be optimal in energy for this process. Generation of epithermal neutrons by several approaches is being studied. The oldest of these uses neutrons from nuclear reactors, but there is also interest in using ~2.5 MeV protons from a radiofrequency quadrupole linac to strike a lithium or beryllium target [5]. Experiments at Paul Scherrer Institute in Switzerland indicate that a suitable neutron spectrum can be generated from 70 MeV protons striking a lead target surrounded by an iron moderator[6].

D. Isotope Production

Facilities that have access to an accelerator for isotope production typically use ^{11}C, ^{13}N, ^{15}O, or ^{18}F for PET imaging. These isotopes can be produced by commercially available cyclotrons. If an accelerator is not available , a hospital can purchase an isotope such as ^{82}Sr to generate ^{82}Rb for PET diagnosis of heart

disease. In the United States the primary sources of these longer-lived parent isotopes are Brookhaven and Los Alamos National Laboratories. PET imaging is becoming a standard diagnostic procedure whose costs are reimbursable by health insurance. When this happens, demand for imaging isotopes will increase and may well exceed present U.S. capabilities.

II. Scenario for a Hospital-Based Facility

A. Motivation for Using a Proton Linac

The usual approach to producing radioisotopes or neutrons for fast neutron therapy has been to use a cyclotron. During the 1970's and 1980's clinical trials of fast neutron therapy were conducted at several institutions in the United States. Cyclotrons are used at all the facilities except Fermilab, which uses a proton linac. At Fermilab, 66 MeV protons not needed for the laboratory's particle research program strike a beryllium target to produce fast neutrons. This is the most intense and highest energy beam in the group of facilities doing NCI-funded research. Fifteen years of clinical and operating experience have led to the following observations:

1. Local control rates are higher and side effects less severe at facilities having higher energy neutrons.
2. The proton linac operates at better than 99% efficiency, with less than one unscheduled down-day per year.
3. The linac dose rate is higher than for cyclotrons, even though the beam is shared with the particle physics program.
4. Linac power costs are one-third to one-half the costs for operating an equivalent cyclotron.
5. Linac operation is inherently cleaner than cyclotron operation in generation of induced radioactivity.

Until recently the technology needed for proton linacs could be found only in research centers like Fermilab. In the twenty years since the Fermilab linac was constructed, there have been significant technical advances. It is now possible to build a linear accelerator that is smaller and less costly, but with at least as good reliability and even higher intensity than the Fermilab linac.

B. Parameters of the Linac

Conceptual design work and feasibility studies for a hospital-based proton linac have been underway for several years. The earlier studies are summarized in reference [7] and the works cited there. Table 1 lists accelerator parameters from a more recent study [8]. The accelerator system consists of a duoplasmatron H^+ source, a low energy beam transport system (LEBT), a radiofrequency quadrupole linac (RFQ), and a drift tube linac (DTL) that can deliver 180 μA average current. Fast neutron therapy requires approximately 90 μA for optimum dose rate and proton therapy requires tens of nanoamps. Isotope production rates are proportional to beam current. Using beam-switching techniques developed and demonstrated at Fermilab, it is possible to share beam simultaneously between proton or fast neutron therapy and isotope production on a pulse-to-pulse basis. BNCT requires the full 180 μA. This precludes other uses of the beam during the time these relatively rare brain tumors are being treated.

The present design allows four linac beam energies, although more gradual variations could be provided by tuning procedures. These energies are achieved by drifting the accelerated beam from a low-energy section through the unexcited downstream sections. The lowest, 21.4 MeV, is appropriate for producing the most common PET isotopes as well as for injection into a synchrotron for acceleration to the higher energies used for proton therapy. The highest, 70.4 MeV is needed for fast neutron therapy, BNCT, and proton therapy for ocular melanomas. The intermediate energies allow for flexibility in isotope production, giving a choice of energy above threshhold for a particular reaction, without approaching the threshhold for unwanted contamination. They may also be useful for as yet unidentified lower-energy proton applications.

C. Description of the Facility

A two-story facility is envisioned, with the examining rooms, offices, PET scanning machines and linac power supplies located on the upper level and treatment rooms and isotope production labs at the basement level, to take advantage of natural earth shielding. Figure 1 presents a schematic plan for the lower level. It shows two treatment rooms for fast neutron therapy, the first of which is also equipped for treating ocular melanomas with 70 MeV protons. A collimator and diffractive scattering system are used to further reduce the

throttled-down beam intensity from microamps to nanoamps for the safety of the patient. In the BNCT room, 70 MeV protons strike an annular lead target embedded in iron, which epithermalizes the neutrons. This targeting scheme is based on studies by B. Larsson and P. Stromberg [9]. Alternatively, the room could be equipped to use an RFQ as a neutron generator, if that should prove to be a superior source of neutrons. Isotope production facilities include a production room and a hot lab for processing the isotopes. An opening in the shielding provides for injection into a synchrotron to accelerate beam up to 250 MeV for proton therapy. No design work has been done on the synchrotron, which provides variable energy output.

The layout is intended to provide flexibility in implementation. Once the linac is installed, one could choose to equip only one treatment room, or only manufacture isotopes, or concentrate on using the linac as an injector to the synchrotron. In this way, construction and equipment costs could be spread over several years.

Conclusions

Proton linac technology has advanced greatly in the last decade. A proton linac has the flexibility and current capabilities required for a modern particle therapy and isotope production facility. It will fit in a room the size of a typical hospital corridor. Twenty years' operating experience at Fermilab show that the technology is mature enough to provide reliable operation in a hospital-based treatment facility. Proton linacs are excellent candidates for neutron and proton sources for the next generation of particle therapy accelerators.

Acknowledgements

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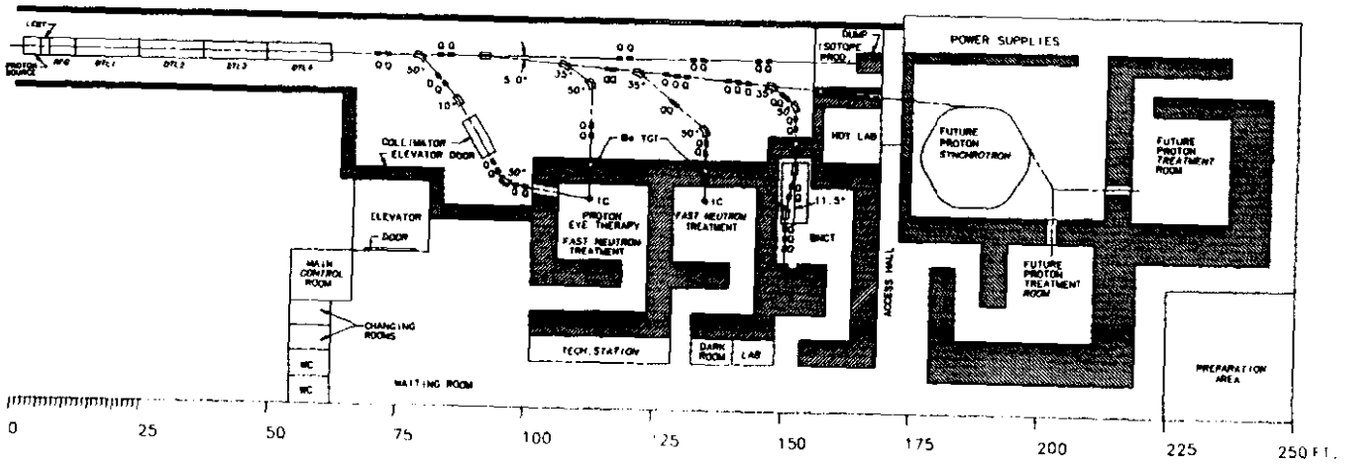
Table 1. Design Parameters of a 70 MeV Medical Proton Linac

Accelerated Ion	H^+	
Maximum Beam Energy	70.4 MeV	MeV
Available Beam Energies	21.4, 38.7, 55.2, 70.4	MeV
Peak Beam Current	40	m A
Beam pulse length	75	μsec
Pulse repetition rate	60	Hz
Average beam intensity	180	μA
RF duty factor	0.66	%
Operating frequency	425	MHz
Peak RF power, including RFQ	9.6	MW
Total input power, including vacuum system	200	kW
Ion source energy	30	keV
RFQ output energy	2	MeV
Accelerator overall length including injector	24.3	m

Figure Caption

Fig. 1. Layout of the lower level of the radiation facility with the linac at the left.



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