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A Hospital-Based Proton Linac for Neutron Therapy and Radioisotope Production*

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Abstract

Fermilab's Alvarez proton linac has been used routinely for neutron therapy since 1976. The Neutron Therapy Facility (NTF) operates in a mode parasitic to the laboratory's high energy physics program, which uses the linac as an injector for a synchrotron. Parasitic operation is possible because the linac delivers ~1.2 x 10^{13} protons per pulse at a 15 Hz rate, while the high energy physics program requires beam at a rate not greater than 0.5 Hz. Protons not needed for physics experiments strike a beryllium target to produce neutrons for neutron therapy. Encouraging clinical results from NTF have led to a study of the issues involved in providing hospitals with a neutron beam of the type available at Fermilab. This paper describes the issues addressed by that study.

Clinical Experience

For over a decade the National Cancer Institute has conducted clinical trials to determine the efficacy of neutrons in the treatment of malignant tumors. Neutron beams at the other facilities participating in the studies were produced by 40 to 50 MeV protons from cyclotrons, while Fermilab used 66 MeV protons from the Fermilab linac. Results established neutron therapy as the treatment of choice for certain tumors known to be resistant to conventional radiation therapy[1][2][3][4]. In addition, it was noted that patients treated at Fermilab have fewer side effects than those treated at the other facilities. This is attributed to the more favorable dose distributions produced by the higher energy neutrons available at Fermilab. Hence, it is desirable for neutron beams similar to the Fermilab beam to be available at hospitals. Until now, the large size of the Cockcroft-Walton pre-injector and the ~60 meter length of the linac used by NTF, as well as the power and maintenance costs, have prohibited duplicating this facility in a hospital setting. However, recent advances in linac technology are making it possible for some hospitals to use a proton linac as a neutron source.

A Modern Proton Linac

Improvements in proton source designs and radiofrequency (rf) systems have dramatically reduced the physical size of a 66 MeV proton linac. Thus, the largest component of a modern 66 MeV linac would be a ~20 meter long cylindrical tank about 40 cm in diameter. A duoplasmatron source, low energy beam transport module (LEBT) and a radiofrequency quadrupole (RFQ) at the upstream end of the linac would bring its length to about 24 meters. An artist's conception of the linac is shown in Figure 1. As has been suggested by the proposers of the PIGMI project[5], such a machine could be located in a tunnel under an existing parking lot at a typical hospital. Power requirements are about 200 kW[6], which compares favorably with the 600 kW required to run a 66 MeV cyclotron for fast neutron therapy[7]. Radiation levels are minimal along the length of the linac and adequate shielding is achieved using ordinary cinder block construction for housing the machine. (Of course, the target area and treatment rooms would require shielding comparable to that used for conventional photon therapy.) Components of the machine are commercially available and are used in other, nonmedical applications so that the first hospital to build the proton linac described here would not be dealing with the problems of repairing and maintaining one-of-a-kind equipment. Thus, it is now realistic to consider more widespread clinical use of a medical proton linac.

In addition to having more favorable power consumption and radiation levels, a linac provides much higher dose rate than a cyclotron and allows for future upgrades to higher energy. At Fermilab, the maximum dose rate at isocenter is 35 cGy/min. The isocenter is 190 cm from the production target to allow for ease in handling the 74 cm long collimators and to facilitate adjustments in the patient's position. Because the dose rate is governed by the inverse square law one could increase the rate by moving the patient closer to the beam. At one time the isocenter was at 153 cm from the target, but this distance was found to be impractical for many patient setups. Hence, in the discussion of dose rate, 190 cm will be used as a reference point. At Fermilab this rate is determined by 57 microsecond-long pulses delivered at a 15 Hz rate with a peak current of 35 mA. By using a source that can provide 50 mA peak current and by operating at 60 Hz it is possible to achieve a 200 cGy/min dose rate. This should be compared with the 30 cGy/min rate at 190 cm available at the medical cyclotron which supplies beam for the University of Washington's neutron facility[7].

Finally, ease in upgrading to a higher proton energy is important because even though 66 MeV protons are known to produce more favorable neutron dose distributions than lower energy beams there is no *a priori* reason to believe that 66 MeV is an optimal energy. A clinician could choose that energy because there is considerable clinical experience at that energy. Nevertheless, it is entirely possible that higher energy neutrons would produce even better distributions. A treatment facility which installed a 66 MeV proton linac could always upgrade to a higher energy by adding another tank. Table I summarizes this comparison between linacs and cyclotrons for neutron production.

Clinical Options

A single tank linac would be satisfactory for simply reproducing the therapy capabilities presently available at Fermilab. However, since the machine is being designed for use in a hospital it is appropriate to consider additional medical applications. Fermilab's experience in switching beam between the neutron therapy and high energy physics programs within a 0.2 second time interval, demonstrates the feasibility of generating radioisotopes concurrently with neutron therapy. A 66 MeV linac is best suited for producing medically useful isotopes such as ^{123}I and ^{127}Xe[10], though the beam could be degraded to produce the isotopes normally obtained from 15 to 20 MeV cyclotrons. Alternately, lower energy protons could be obtained by building the drift

	LINAC	CYCLOTRON
Power usage	200 kW	600 kW
Radiation levels	minimal	high
Dose rate at 190 cm	200 rad/min	30 rad/min
Upgrade to higher energy	possible	not possible

Table 1: Comparison between linacs and cyclotrons for neutron production using a 66 MeV proton beam.

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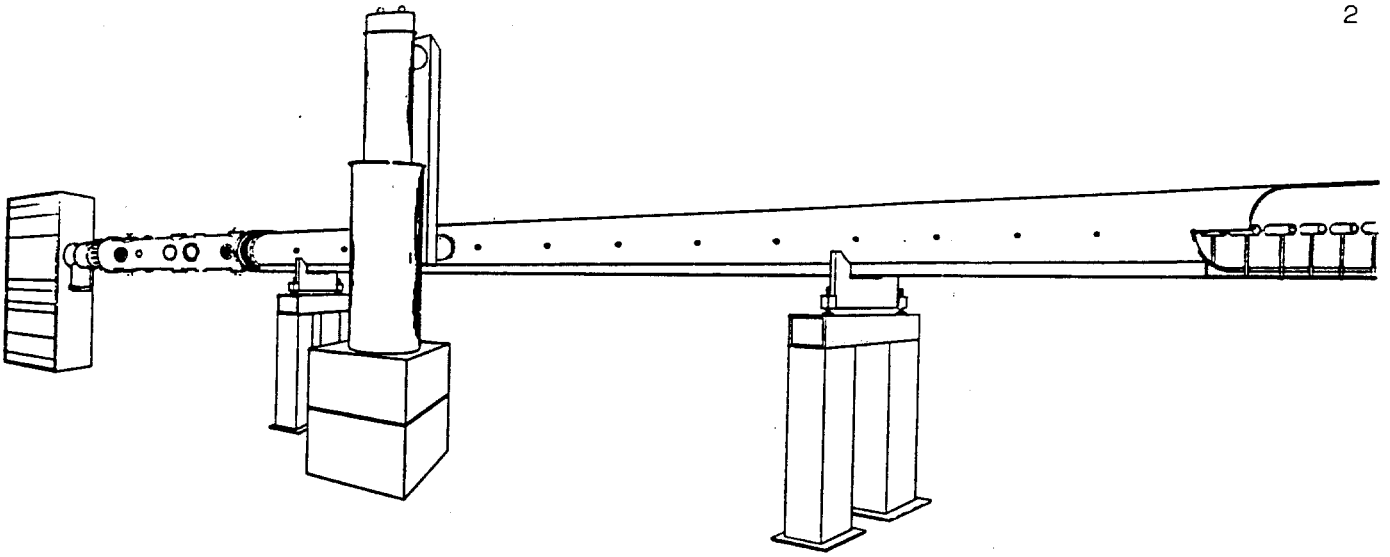

Figure 1: Artist's conception of a medical proton linac including source, LEBT, RFQ, drift tube linac, and power amplifier.

tube linac in two sections and turning off the accelerating gradients in the downstream tank during isotope production cycles.

A second application involves generating epithermal neutrons to treat brain tumors using boron neutron capture therapy[11]. One possibility is to use 2.3 MeV protons on a lithium production target[8]. Recently, a 2.0 MeV RFQ was designed and constructed as an injector for a medical proton synchrotron[9]. A similar RFQ operating at the slightly higher energy, 2.3 MeV, could be used to produce nearly epithermal neutrons in addition to acting as an injector for the proton linac. This method of generating epithermal neutrons is more economical than using neutrons from a reactor. In addition, the machine is relatively portable and requires much less radiation shielding than is needed for a nuclear reactor.

The simple, single-tank design as well as the options for producing isotopes and epithermal neutrons have been the subject of a design study which is reported elsewhere[12]. This study found that all of the options described above are technically feasible and it established a set of machine design parameters for each of them.

Conclusion

Recent advances in linac technology make it possible to use a proton linac for neutron therapy in a hospital setting, and clinical studies over the last decade indicate that it is appropriate to do so.

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