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A COMPACT PROTON LINAC FOR FAST NEUTRON CANCER THERAPY

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ABSTRACT

The successful operation of Fermilab's proton linac for fast neutron cancer therapy has prompted the design of a proton linac appropriate for use in a dedicated clinical setting. In addition to including and improving the clinical parameters of the Fermilab linac, the compact linac described here also serves as an injector for a proton therapy synchrotron and provides beam for medical isotope production.

I. INTRODUCTION

During the past quarter-century, worldwide clinical trials have established the role of fast neutron therapy in the treatment of radioresistant tumors.[1] It is important to make this treatment more accessible to patients by establishing more clinics capable of providing the therapy. To this end, a hospital-based proton linac for particle therapy was proposed in the late 1980's.[2,3] Since that time a great deal of progress has been made in the technological and engineering aspects of proton linacs. The system described here is an update of our earlier work. It is an economical linac that can be the heart of a clinic dedicated to treating cancers that do not respond to conventional radiation therapy. In addition, it can be used to generate isotopes used in diagnosing tumors and in monitoring the progress of their treatment.

II. PARAMETERS OF THE LINAC

The performance specifications of the compact Model PL-66 linac are listed in Table I. The maximum proton energy of 66 MeV was chosen to match the energy of the clinical neutron beam in use at Fermilab, where neutrons are produced by allowing 66 MeV protons to strike a beryllium production target. The lowest energy is 7 MeV, the output energy of the Model PL-7 linac used as an injector to a 66 MeV drift tube linac (DTL). The Model PL-7 technology is well established, and several of these devices are already in use at research centers. These compact accelerators replace the large Cockroft-Walton accelerators that have historically served as injectors for proton linacs. They use a standard duoplasmatron source to inject a 30 keV beam into a 425 MHz radio frequency quadrupole (RFQ) structure that bunches the beam and accelerates the protons up to 3 MeV. The 3 MeV beam is then injected into a 425 MHz ramped-gradient drift tube linac (RGDTL) that accelerates it to 7 MeV. Figure 1 is a photograph of the PL-7 linac.

The DTL portion of the PL-66 linac uses three constant gradient tanks to accelerate the 7 MeV protons to 66 MeV. The linac operates at a 30 Hz rate, with 315 microsecond long pulses of 20 milliampere beam current,

Table I. Model PL-66 Linac Performance Specifications

Accelerated ions	H^+	
Linac input energy	30	keV
RFQ output energy	3.0	MeV
Available beam energies	7,27,47,66	MeV
Linac output current (pulsed)	20	mA
Maximum beam pulse width	315	μsec
Maximum pulse repetition rate	30	Hz
Maximum average beam current	190	μA
Peak rf power requirement	7.6	MW
Maximum rf duty factor	1.05	%
Model PL-7 injector linac length	4.4	m
Drift tube linac length	16.1	m
Total linac length	20.5	m
AC input power	<200	kVA
Linac mass	260	kg/m

*Operated by Universities Research Association Inc., for the U. S. Department of Energy, under contract #DE-AC02-76HO3000

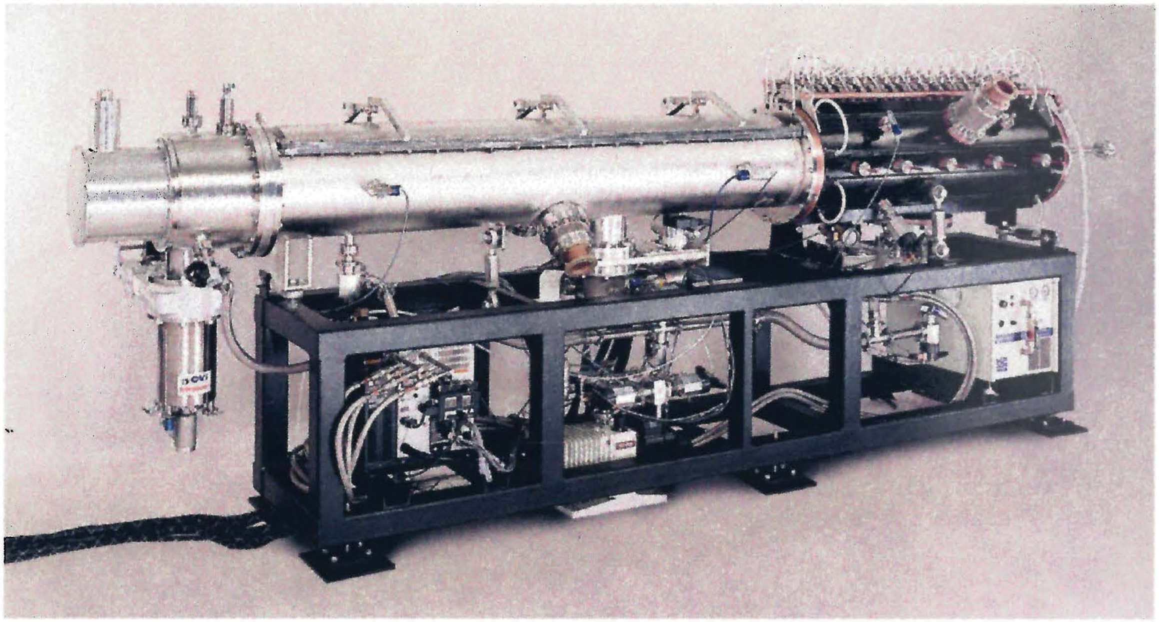

Figure 1. The Model PL-7 linac used to inject 7 MeV protons into the 66 MeV drift tube linac as well as providing 7 MeV protons to produce isotopes for PET scanning.

corresponding to 0.95% beam duty factor. The peak power required is 7.6 MW, with AC operation power of less than 200 kW. Permanent-magnet quadrupoles installed in each drift tube are used to focus the beam through the structure and to minimize the beam emittance growth. To minimize beam spill along the structure, the size of the beam aperture increases from 12 mm in the first tank to 16 mm in the last tank.

The DTL was optimized to achieve the minimum length consistent with routinely achievable accelerating gradients and available radiofrequency (rf) power systems, accelerating the beam from 7 to 66 MeV in a length of 16.1 meters. Each tank is powered by a 4 MW (peak), 425°MHz klystron like the ones used for the 70 MeV SSC linac now being operated by International Isotope, Inc. for radioisotope production. Proven linac sub-systems were used in the specification of this system to provide the most practical design with the minimum capital cost, which is now estimated to be less than $7.0 M. Major parameters of the three DTL tanks are listed in Table II and a sketch of the PL-66 linac is shown in figure 2.

III. DISCUSSION

In designing this compact linac careful consideration was given to the operating experience acquired during more than twenty years of treating patients at the Fermilab Neutron Therapy Facility (NTF) using the Fermilab linac. Though the dose rate at NTF is higher than the dose rates at clinics that use cyclotrons, it is still lower than that achieved with conventional photon therapy. This compact linac has a lower peak current than is available at NTF, but the higher beam duty factor and repetition rate lead to a dose rate that is comparable to conventional therapy. The 7.6 MW peak power requirement compares favorably with NTF s 11 MW peak power requirement. The use of permanent magnet quadrupoles, rather than pulsed electromagnetic quadrupoles, also reduces the electrical power costs.

State of the art research in cancer therapy uses positron emission tomography (PET) scanning to locate tumors and to study the effect of radiation on tumors. The most important isotopes for this purpose are short-lived. Hence it is necessary to have the isotope production equipment physically close to the scanning equipment.

Isotopes such as ^{11}C, ^{13}N, ^{15}O and ^{18}F can be produced using 7 MeV protons extracted from the PL-7 linac. A small dipole magnet located between the exit of the PL-7 and the entrance to the DTL can be pulsed to divert beam away from the DTL to isotope production targets. A dipole magnet at the exit of the DTL can direct beam to a neutron therapy treatment room or into a synchrotron where it could be accelerated to higher energies for proton therapy. In addition, the 66 MeV beam could be used to manufacture longer lived medically useful isotopes that could be shipped to other medical facilities.

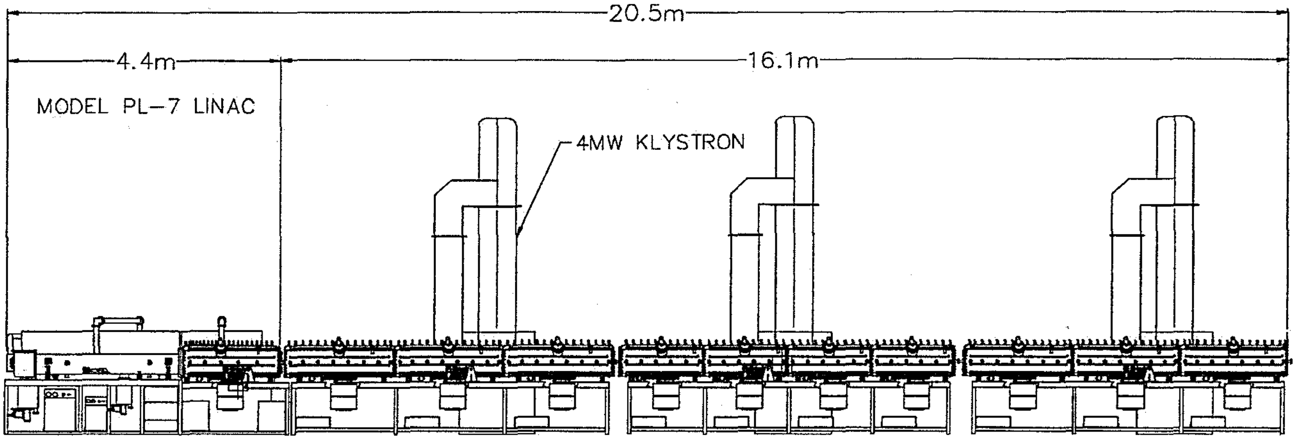

Figure 2. The Model PL-66 linac including the PL-7 injector, three drift tube tanks and their associated klystrons.

In summary, the compact proton linac described here is well suited to supporting two forms of hadron therapy as well as state of the art research in PET imaging.

REFERENCES

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Table 2. Parameters of the constant gradient drift tube linac.

	Tank 1	**Tank 2**	**Tank 3**	
Operating frequency	425	425	425	MHz
Input beam energy	7.0	27.0	47.4	MeV
Output beam energy	27.0	47.4	66.0	MeV
Length	5.27	5.36	5.15	m
Number of drift tubes	41	27	21	
Aperture radius	6	7	8	mm
Accelerating field gradient	4.2 — 4.83	4.86	4.89	MV/m
Permanent magnet quadrupole gradient	155	105	105	T/m
Structure power (peak)	1.73	1.97	2.05	MW
Beam power (@ 20 mA) (peak)	0.4	0.41	0.37	MW
Total rf power (peak)	2.13	2.38	2.42	MW
Structure dissipation (average)	18	21	21.5	kW