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INITIAL PERFORMANCE OF THE PIGMI PROTOTYPE*

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Abstract

The PIGMI (Pion Generator for Medical Irradiations) program* at LASL is an accelerator development program aimed at completing the design of an accelerator suitable for use as a pion generator in a hospital-based radiotherapy program. The major thrust of the program has been the design of a 7 MeV prototype accelerator which emphasizes compactness, economy of construction and operation, and reliability. To achieve these goals the design of the prototype has exploited a number of innovations in proton linac technology. An overview of the program discussing the major innovative features of the prototype is presented. The initial operating experience is discussed and initial performance measurements are presented.

Introduction

At the Los Alamos Meson Physics Facility (LAMPF) clinical and biological experiments are currently being conducted to determine the effectiveness of negative pi mesons (pions) for use in the treatment of cancer.[1] At other laboratories similar clinical trials are currently underway using neutrons, protons and heavy ions in cancer therapy. The sources of radiations in most cases are large particle accelerators which have been developed by physicists as tools for studying the structure of matter and are not necessarily relevant for broader medical applications. It appears likely now that as these clinical evaluation programs near completion a demand will be created for medically practical sources of some of these particles.

In recent years accelerator technology has grown rapidly and linacs in particular now appear to be very attractive sources of particles for radiotherapy. Linacs are capable of accelerating high currents with very low beam loss and exhibit a relatively high ac power to beam power conversion efficiency. Aware of these facts, the National Cancer Institute (NCI) has funded the PIGMI program at LASL to develop the design for a generator of pion beams having sufficient quality and intensity for use in radiotherapy.

The PIGMI program is an accelerator development program designed to pursue certain innovations in proton linac technology which would lead to the design of an accelerator suitable for medical use in a hospital environment.[2] The major thrust of the program has been the design and testing of a 7.3 MeV prototype accelerator which incorporates innovations in accelerator technology which allow a more compact design, reduced construction cost, higher reliability and simplicity of operation. The program is now in the final year of its three-year grant period. All of the design work is complete, and fabrication of the final accelerator components is in progress. The injector and control systems are complete and are operating reliably. A 450 MHz klystron power supply has been assembled and has powered a test cavity at field gradients exceeding those required for the prototype accelerator. The first accelerator section has been assembled and is ready to be powered with beam tests expected to follow shortly. The major features of the PIGMI prototype accelerator are shown in Fig. 1.

Injector System

The 250 keV injector portion of the PIGMI prototype incorporates several innovative features which provide a compact, relatively inexpensive system.[3] The high voltage is generated by a commercial 300 KV, 1.4 mA Cockroft-Walton power supply. The equipment dome which houses the power supplies, controls and utilities for the ion source, is constructed of three short electronics racks which rest atop a set of insulating legs made of PVC sewer pipe. Rings have been mounted along the top and bottom edges of the dome to suppress corona. Power is supplied to the equipment dome via a 300 KV, 5 KVA oil-insulated isolation transformer.

The accelerating column assembly includes an ion source and accelerating electrodes mounted inside a glued ceramic column which is cantilevered from a grounded support stand. The short high-gradient column employs spherical electrodes designed to produce a beam which converges to a waist at the location of the buncher gap. The injector will be pumped from ground potential by a 500 ℓ/sec turbomolecular pump. An insulated "snout" connects the dome to the ion source which supports the water, gas and electrical lines. Each of these lines is wound around the snout to form an inductor between the high voltage supply and the accelerating column. This feature of the injector has substantially reduced the arc-down rate as well as reduced the amount of energy dissipated during a spark. Using a conventional duoplasmation ion source, this injector provides the required 50 mA of protons at a 0.36% duty factor.

Transport System

Because the initial alternating phase-focused (APF) section of the linac preserves a circular beam, no quadrupole matching elements are necessary in the transport system. This region is therefore relatively short. The first element in the transport system is a double harmonic, single cavity buncher which is located a few centimeters from the exit aperture of the column at the point where the beam is focused to a waist by the column optics. This cavity has the novel feature that it can be excited at both the fundamental frequency of the linac, 450 MHz in the TM_{010} mode and at the first harmonic of 900 MHz in the TM_{020} mode. By proper excitation and phasing of these two modes the net bunching can be made extremely linear over a 220-degree range in phase, thereby minimizing the "bow-tie emittance growth" normally associated with buncher systems.[4]

The proton beam is refocused to a waist at the linac entrance by a single magnetic solenoid lens having a nominal focal length of 19 cm. In order to provide as much space as possible for beam diagnostics equipment, the length of the solenoid magnet design was held to a minimum. The finished magnet features a nickel-plated low carbon steel core assembly with removable pole pieces of heat-treated cobalt-vanadium steel, a high permeability alloy. The coil assembly consists of two copper tape-wound sections with thin stainless steel cooling panels on each end. A thin coat of epoxy on the edges of the conductor and an arc-sprayed Al_2O_3 coating on the cooling panels provides the electrical ground insulation.

The bore and face of both the buncher and the solenoid are sealed and finished so that special beam diagnostic boxes can be mounted directly without the necessity of intermediate pipes and flanges.

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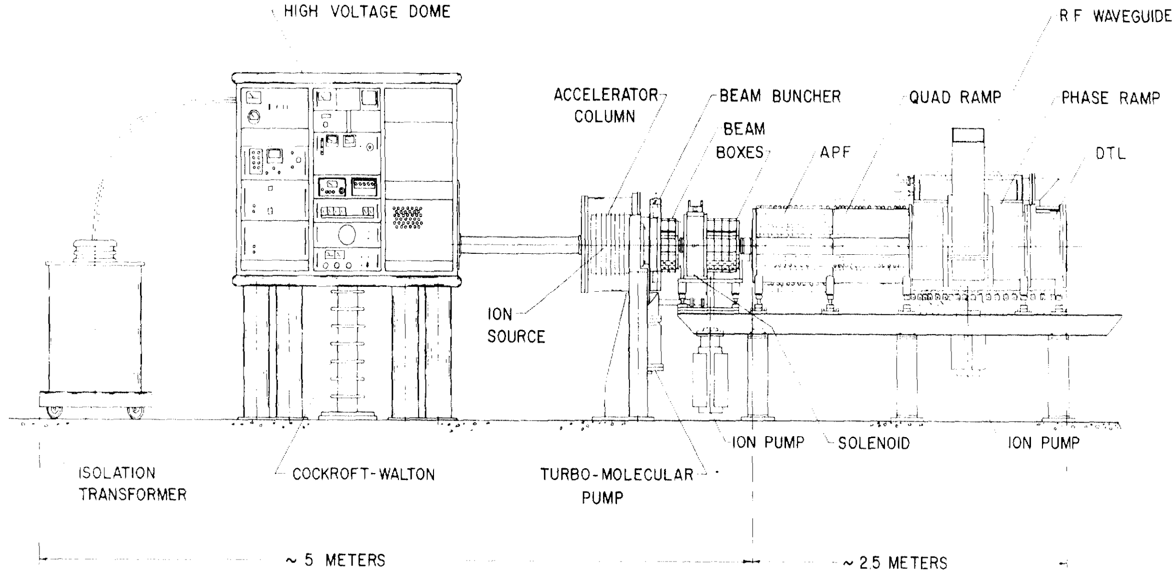

LINAC PARAMETERS	
INJECTION ENERGY	250 keV
FINAL ENERGY	7.32 MeV
FREQUENCY	450 MHz
GRADIENT	6 MV/m

BEAM PARAMETERS	
PEAK CURRENT	30 mA
PULSE LENGTH	10 μs
REPETITION RATE	360 Hz
AVERAGE CURRENT	100 μA
DUTY	.36 %

Fig. 1. PIGMI Prototype Accelerator.

The properties of the injected beam are evaluated with the aid of intercepting beam probes attached to both pneumatic and stepping motor actuators which are mounted on the beam diagnostic boxes. The boxes themselves are self-aligning on the beam line and are easily interchangeable for convenient servicing of the diagnostic devices.

The diagnostic equipment currently in use for injector beam studies includes a ruby viewing screen, multi-wire and wire scanner profile monitors, emittance measuring hardware, four jaw apertures, beam current transformers and Faraday cups. In order to dissipate the power of the intercepted beam many of these devices are cooled by means of vacuum-sealed heat pipes attached to air cooled radiators.

Linac

The linac portion of the PIGMI prototype consists of a single tank, loaded with 64 drift tubes, which accelerates the proton beam from 0.25 MeV to 7.32 MeV in a total length of 2.48 meters. The tank is divided into four sections, each constructed of bright copper plated mild steel designed to resonate at 450 MHz.

The first section, which is now complete and contains no quadrupole lenses among its 28 drift tubes, is entirely dependent on the APF principle for beam confinement.[5] The last section is a scaled-down version of a conventional quadrupole focused Drift Tube Linac (DTL). This section, containing only four drift tubes, accelerates beam from 5.89 MeV to 7.32 MeV at an average rate of better than 5 MeV/meter.

The middle two sections form a transition between the APF and DTL sections. In the Quad Ramp section, permanent-magnet quadrupole lenses are introduced into every other drift tube in a +0-0 sequence. In the Phase Ramp section, the gap phases are rapidly transformed from the APF sequence to a constant stable phase angle of -20° suitable for the DTL section.

In the design of the transition region, where there is a mix of both APF and quadrupole focusing, considerable care was taken to keep the transverse acceptance in the horizontal and vertical planes similar. This insures that the beam will experience a smooth transition from the APF region where it maintains a circular shape to the DTL section where its shape is longitudinally modulated by the periodic quadrupole focusing.[6]

Permanent Magnet Quadrupoles

Eighteen of the drift tubes in the PIGMI Prototype will contain permanent magnet quadrupole lenses ranging in strength from 0.95 kG/cm to 7.0 kG/cm. The shortest lens, having the maximum gradient, is only 8 cm in diameter, 2.1 cm long and has a bore radius of 0.6 cm. The design of these compact high field lenses was aided by the code PANDIRA, a program which solves anisotropic magnetostatic circuits by a "direct method" algorithm.

The PIGMI quadrupoles are being fabricated from cylinders of samarium cobalt HICOREX 18 and HICOREX 22 which are magnetized across their diameter. The four circular poles are held in place by a stainless steel yoke with an iron collar. Each quadrupole is individually "tuned" by grinding flats on the circular tips, thereby increasing the aperture while decreasing the field. The resulting flat-tip pole geometry has the remarkable benefit that the multipole harmonics are reduced over the circular pole geometry. The resulting compact magnets can not only achieve the required gradients but, in the worst case, all harmonics are measured to be less than 0.5% of the quadrupole field at a radius of 0.6 cm.

Control System

The control and data acquisition system which is a part of the PIGMI prototype is designed primarily to support an experimental program to evaluate the performance of the prototype accelerator.[7] It has, in addition, a second purpose: to serve as a prototype itself for a hospital-oriented control system. In addition, therefore, to providing hardware and software which support beam diagnostic measurements, techniques are being investigated which will provide a high reliability turnkey approach for accelerator control.

The basic configuration of the PIGMI control system features a central mini-computer which communicates with an array of microprocessor-based local control stations (MPC's) via fast parallel links. Communication with the MPC located in the high voltage equipment dome is routed serially over optical fibers.

Each MPC provides dedicated support for a limited set of control functions, i.e., the console MPC supports only the console, the dome MPC only the dome equipment, etc. MPC's communicate with the control computer only as required to transmit or retrieve data, answer queries or acknowledge commands and to alert the system to situations requiring attention. MPC's interact primarily with equipment interface chasses (EIC's) which contain electronics interfacing directly to accelerator equipment, i.e., magnet power supplies, beam diagnostic probes, etc.

This modular control system with distributed intelligence provides many advantages in the areas of reliability, simplicity and maintainability. Since each MPC interacts with only a subset of linac parameters, the software is relatively simple and with the exception of special modules associated with specific equipment, is interchangeable among MPC's.

Initial Measurements

The accelerating field gradients required in the PIGMI Prototype (6 MV/m) are higher than those ever achieved in a proton linac. In order to verify the feasibility of such high fields, a pre-prototype test cavity dubbed "PIGLET" was built and tested at high power. This 6-cell, 450 MHz cavity, having a 45 MeV DTL geometry was constructed of bright copper plated, stainless steel and served as a guinea pig for many of the fabrication techniques later used in the PIGMI Prototype.

PIGLET has been powered at the design level of 6 MV/m and at fields exceeding 8 MV/m. The field gradients were inferred from measurements of power and Q using the shunt impedance calculated by the SUPERFISH cavity code.

Fields in excess of 6 MV/m were verified using an independent and unique measurement technique. A thermal electron source and battery were packaged to fit into the bore of the last full drift tube. Electrons accelerated across the last gap were allowed to exit from the cavity through a 0.13 mm Kapton window. After being deflected through a 60° bend the electrons were stopped in a super-pure germanium detector where the energy spectrum was measured with a multichannel pulse-height analyzer. The expected electron energy gain as a function of the accelerating field in the PIGLET geometry was calculated by means of a gap integration program written for the purpose. Electron energies of 1.3 MeV were measured corresponding to an average axial field of 6.6 MV/m. Because of the peak power output limitation of the klystron used to drive PIGLET, a limiting value for the electric field was not found.

Measurements of the beam properties in the transport region indicate that the injector is operating properly. The normalized emittance of a 40 mA beam has been measured to be 0.05 cm mrad, yielding a brightness value of 3.2 $A/cm^2 mrad^2$. By transforming the measured emittance backward through the buncher one finds that the beam fills only 75% of the buncher aperture as expected. By varying the solenoid magnet we have been able to achieve the beam spot size required for injection into the linac.

Conclusion

The primary objective in the construction and testing of the PIGMI Prototype accelerator is to establish a proof principle for its various innovative features. A pion generator for cancer therapy using an accelerator incorporating these features would be on the order of 120 meters long, having a terminal energy of 650 MeV and an average beam current of 100 μA. Such a facility, costing between $10 and $15 million, would be much more expensive than conventional radiotherapy equipment but would still represent a small fraction of the $30 billion annually spent on cancer care. A modest number of pion facilities, perhaps ten to twenty, might be justified if pion therapy were able to save just 15% (9,000 patients) of those 60,000 cancer patients who die annually of local disease. The cost for maintaining a cancer patient who eventually dies is estimated to be $20,000 greater than the cost of curing one.[8] At that rate 9,000 additional cures would represent an annual savings of $180 million.

In addition to pion therapy the PIGMI technology has applications in related areas, including radioisotope production, proton, neutron and heavy ion radiotherapy, and proton tomography.

Acknowledgments

Those people having primary responsibility for the PIGMI Prototype project reported above included D. A. Swenson, L. D. Hansborough, S. F. Klosterbuer, and R. W. Hamm.

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