LOMA LINDA MEDICAL ACCELERATOR PROJECT

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In the winter of 1986, the Chairman of the Radiation Sciences Department of Loma Linda University Medical Center, Loma Linda, California asked the Fermi National Accelerator Laboratory to design a 250 MeV proton accelerator which would be suitable for a proton therapy facility for treatment of cancer and other diseases in the hospital. An agreement was approved by the U.S. Department of Energy as a technology transfer project under which Fermilab presented a conceptual design in June of 1986 to LLUMC for their approval. Following this preliminary design a detailed design was developed which was presented to LLUMC in May of 1987 and construction of the accelerator then was authorized.

In late December 1988, the first 2.0 MeV beam was injected into and accelerated in the synchrotron. By January 10, 1989 protons had been accelerated to the design maximum energy of 250 MeV. This operation was accomplished in a temporary shielding enclosure within a Fermilab shop building using an entire complement of borrowed power supplies which have been adapted for this purpose. Figure 1 in a photograph of the accelerator as it is being commissioned at Fermilab.

The Application

The installation of the Proton Accelerator in the

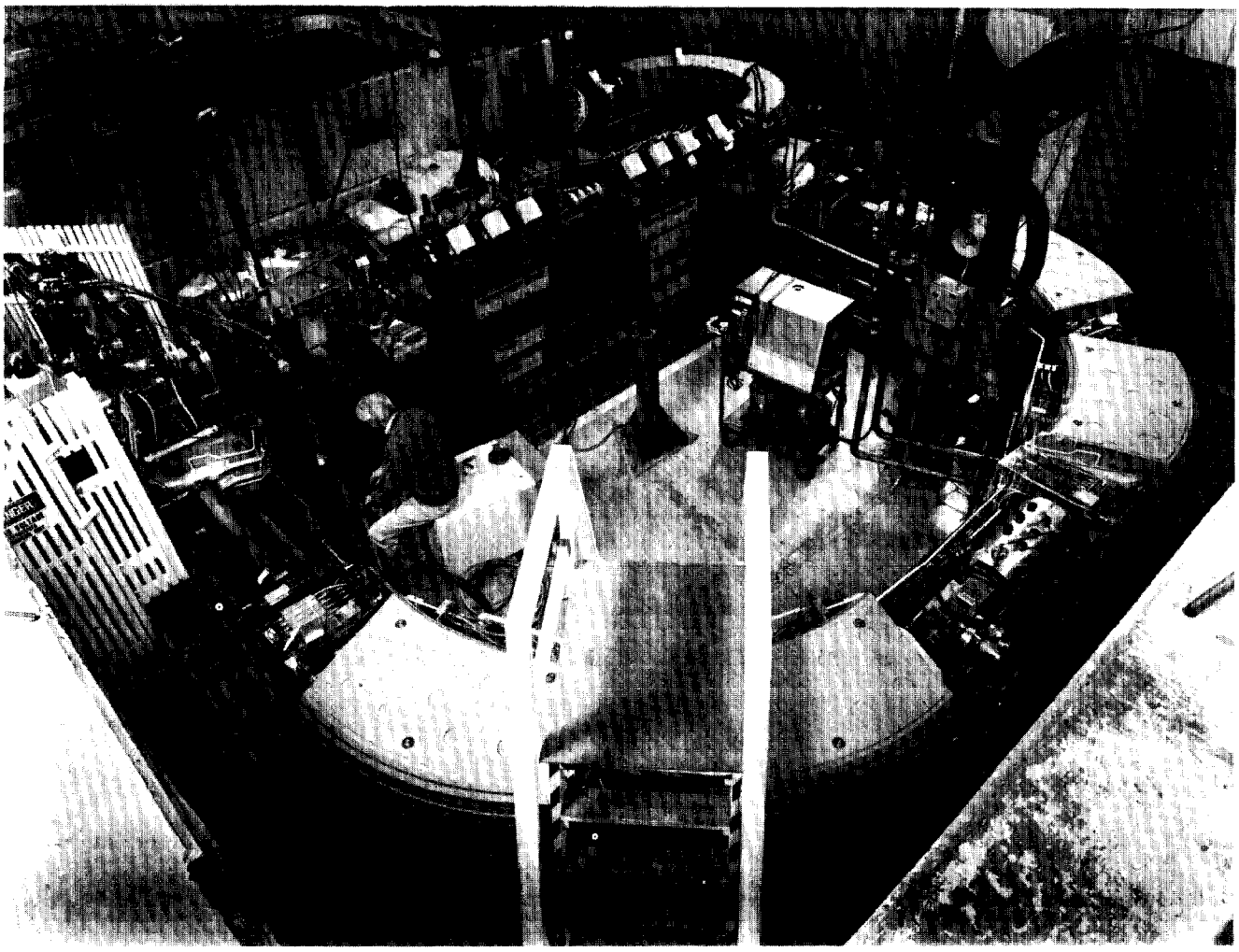

Figure 1. The Loma Linda 250 MeV Proton Synchrotron installed at Fermilab.

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hospital Radiation Oncology facility will constitute a major advance in radiation therapy. The biological effect of the Proton Beam on cancer cells is similar to other more widely-used types of radiation. The distinct advantage of the use of protons lies in the superior manner in which the beam can be focused on a tumor. Figure 2 is a comparison of the depth dose distributions in tissues for the most commonly used sources of radiation therapy (X-rays, rays and electron beams) as compared to proton beams.

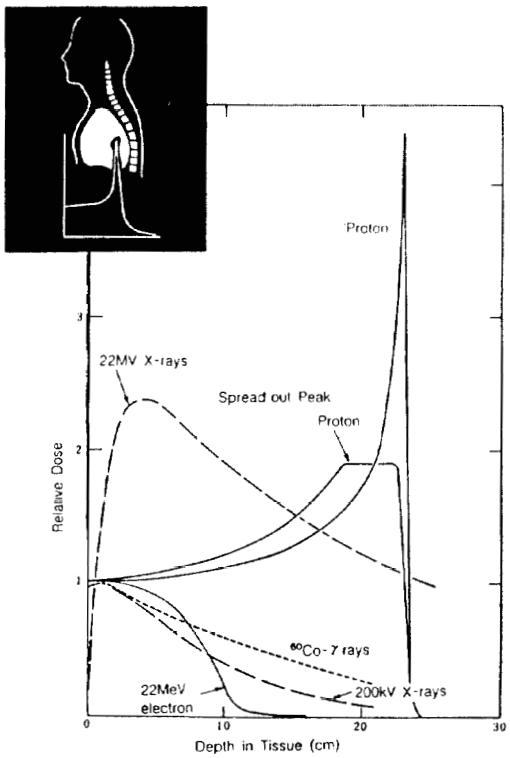

Figure 2. Comparison of depth dose distribution for X-, Y-ray and electron beam with proton beam.

With any kind of radiation treatment the physician must take into consideration the way in which the treatment beam enters the patient's body. With conventional radio therapy the major portion of the radiation is absorbed near the surface and decreases as the beam penetrates further into the tissue. Therefore, in most cases normal tissues in the path of the beam may be injured. This problem can be partially alleviated by dividing the treatment dosage and delivering fractions of it from different angles. In this way damage to normal tissue is minimized as much as possible. Figure 3 illustrates the relative dose deposited in tissue as X-rays from Cobalt 60 pass from left to right through a body containing a cancerous tumor.

Another problem with conventional X-ray is that because of the absorption characteristics of the X-ray beam, residual radiation will pass through the tumor and affect normal tissue on the other side.

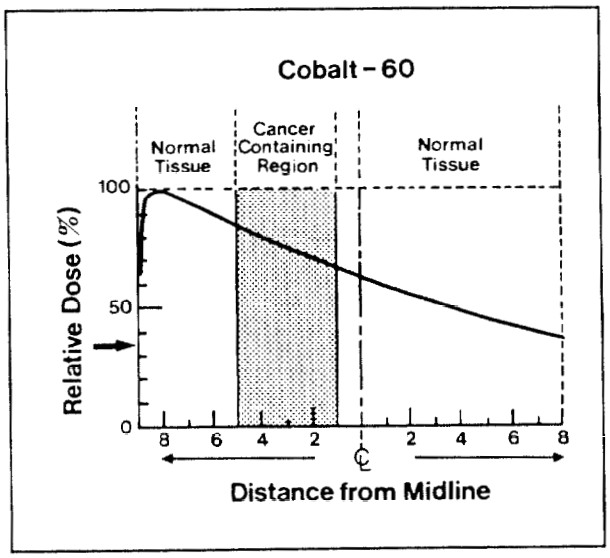

Figure 3. Relative dose vs. depth in tissue for gamma ray beam from cobalt 60. (Gamma rays enter from left to right.)

The proton beam diminishes these problems dramatically. Instead of being absorbed in a high rate at the entry point, the proton beam enters the body at a very low absorption rate and increases sharply at a specific point called a Bragg peak. (Figure 4 shows the Bragg peak in tissue with the protons entering from left to right. By controlling the energy of the beam the therapist can create a series of Bragg peaks directly at the tumor site.

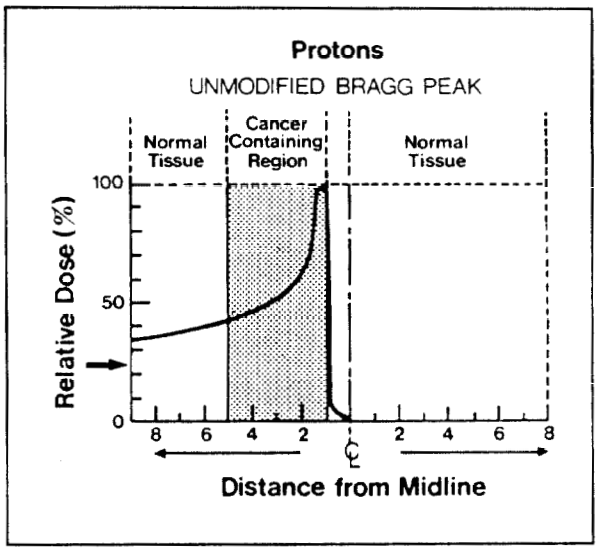

Figure 4. Relative dose vs. depth in tissue for 185 MeV protons. (Protons enter from left to right.)

Therefore the percentage of the dose absorbed by normal tissue is small, while the tumor receives the greatest share (Figure 5).

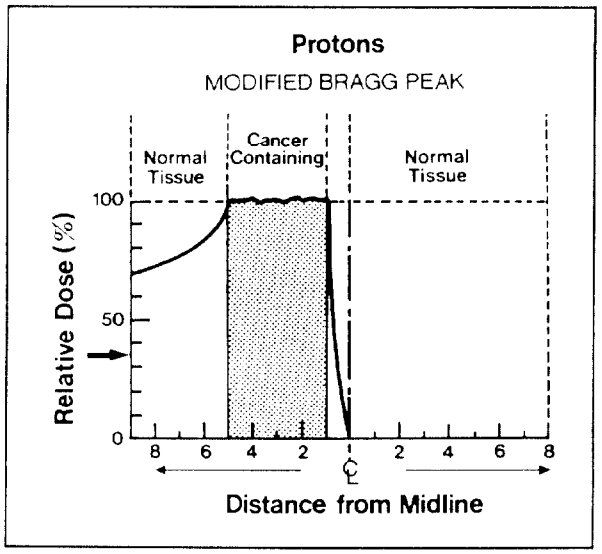

Figure 5. Relative dose vs. depth in tissue for energy modulated protons. (Protons enter from left to right.)

Also the proton beam stops in a very short distance. At the end of the Bragg peak the energy of the beam is completely dissipated, therefore causing no damage to normal tissue behind the tumor.

The Bragg peak exists because the proton is a charged particle. This, of course, represents another advantage in that charged particles can be focused transversely by electromagnetic focusing devices, whereas X-rays and neutrons can only be collimated by shaped holes in absorbers. Thus charged particle beams can be precisely focused longitudinally (by adjusting the cut-off depth of the Bragg peak using a bolus) and transversely by electromagnetic means, thus containing the maximum radiation dose within only the tumor volume.

This precision in focusing makes it possible to treat tumors that have been traditionally very difficult to radiate, such as those next to particularly sensitive structures like the spinal cord. The radiation therapist can paint the tumor with the proton beam with relatively little detrimental effect to the normal structures surrounding it.

Treatment for a tumor such as an oculomelanoma (a tumor in the globe of the eye) has consisted of the removal of the entire eye. With the proton beam the therapist can treat only the tumor and save the eye itself. Because of its superior focussing ability, proton beam treatment for some tumors can also be very short. A normal course of treatment for a small tumor could probably be done in a week or less as opposed to a six- or eight-week treatment plan for conventional therapy. A shortened course of treatment is very beneficial to the patient. The reasoning behind longer treatment schedules goes back to the detrimental effect of traditional X-rays on normal tissues. More time between treatments allows for regeneration of affected normal tissue, lessening the overall negative effect of the treatment. However, that same time will also allow the tumor to regenerate, causing an overall decrease of the effectiveness of the treatment.

Previous Treatment Experience

Experimental, and more recently clinical, use of protons for therapy has been dramatically successful in the United States at the Harvard Cyclotron Laboratory, where physicians from the Massachusetts General Hospital treat patients, and the Lawrence Berkeley Laboratory where heavier charged particles (from Helium to Silicon) have also been used for treatment.

Other research centers in the world that have treated patients include: Uppsala University in Sweden; SIN Laboratory in Villigen, Switzerland; ITEP in Moscow, USSR; Gatchina Laboratory in Leningrad, USSR; KEK Laboratory in Tsukuba, Japan; and Chiba Laboratory in Chiba, Japan.

Each of these institutions which are research facilities which have imposed limitations on the number of patients treated and the number of disease sites so far investigated. Nevertheless treatments have been reported on over 6,000 patients with very encouraging results. This accumulated experience has been the basis for Loma Linda University Medical Center's making the decision to build the first hospital based, multiple treatment room facility, implemented with gantries to make the treatment available to a larger number of patients and greatly expand the number of treated tumor sites. It is expected that these treatments will result in a larger percentage of tumor control coupled with fewer and less debilitating side effects.

The Accelerator

In the proceedings of the 1987 Particle Accelerator Conference, L. C. Teng presented a paper describing the characteristics of the accelerator system which was designed for the Loma Linda Medical Center. This paper will concentrate, therefore, only on those items which have been changed since that time and report on the implementation of the system which has now been put into operation.

The most significant single change is the rearrangement of the injection system to incorporate the injector accelerator (ion source and RFQ) and the matching system into the inside of the synchrotron ring. The introduction of additional quadrupoles and a bending magnet with magnetic gradient has allowed the beam to be matched to all lattice characteristics.

The ion source currently being used is a modified duoplasmotron which was used at Fermilab before the initiation of negative ion acceleration for stripping injection into the booster system. This ion source was originally developed by Cyril Curtis who has been an active physicist in the design, construction and development of the Loma Linda system. The electronics associated with this source have been upgraded by AccSys Technology, Incorporated, in Pleasanton, California. Tests of the upgraded system are now in progress.

The ion source currently has also been replicated by AccSys as a commercial version of the Fermilab ion source. This system produces 50 Ma, or more, of 30

KeV protons with a pulse length of 20 to 50 micro seconds and a repetition rate of 5 pulses per second or more.

The low energy beam transport consists of two solenoid magnets separated by a drift space of about one-half meter.

The RFQ accelerator is a vane type radiofrequency quadrupole cavity which was designed and built by AccSys Technology (Figure 6). This RFQ produces up to 35 milliamps of protons within the required emittance and energy spread requirements to match the synchrotron. A debuncher system has also been built by AccSys Technology, but this system has not been installed at the time of this writing. The transport and matching system incorporates a 180 degree bending magnet with gradient, which adjusts the beam size and shape to the dimensions desired by the synchrotron.

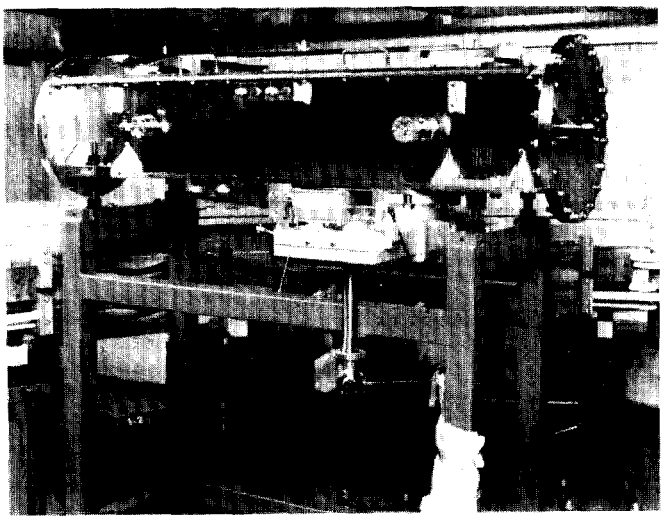

Figure 6. Loma Linda 2.0 MeV RFQ.

Injection into the synchrotron follows a vertical translation through a pair of bending magnets, the second of which is a 20 degree single-turn pulsed septum magnet. The final 5 degree kick is supplied by an electric field kicker between parallel plates above and below the synchrotron aperture. Power supplies for these components of the system were designed and built by Science Application International Corporation.

The accelerating cavity for the synchrotron is a ferrite loaded cavity very similar in design to those used in the antiproton source at Fermilab. This cavity is pictured in Figure 7 and the wide band solid state amplifier which drives it is a commercial unit provided for this purpose.

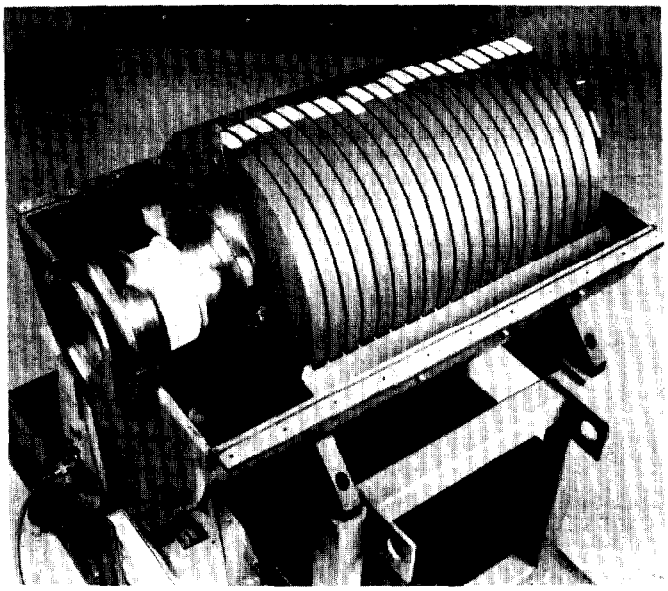

Figure 7. Synchrotron Accelerating Cavity (top removed).

The extraction system is composed of a set of four trim quadrupoles located at 90 degree from one another around the synchrotron circumference in the short straight sections and an electrostatic septum 90 degrees ahead of a magnetic lambertson extraction magnet. This magnet bends the beam vertically out of the synchrotron orbit to miss the next downstream ring magnet.

The Treatment Facility

The treatment facility is being implemented very nearly as described by Teng. The major difference is that the gantries, which rotate the beam so that it may be brought to the patient are being implemented to accommodate an optical design first described by Andrew Sessler of the Harvard Cyclotron, Cambridge, Massachusetts. This gantry design incorporates two achromatic bending systems which change the direction of the beam from a plane parallel to the beam transport axis into a plane orthogonal to that axis.

This mechanical design of the gantries was implemented by Science Applications International Corporation and they are being fabricated by Martinez & Turek, a large aerospace industrial machine shop in Riverside, California.

The Status of the Project

The accelerator has been initially operated and tested at Fermilab. To date these tests have indicated some areas which require additional attention in order to meet the design goals for the accelerator. Extraction has been achieved but improved instrumentation of the low intensity proton beam being extracted is needed to provide feedback signals to achieve the uniform extraction desired for treatment. The desired intensity has not been achieved and efforts are under way to improve this

situation. Improvement is required in the optical match between the ion source and the RFQ. To accomplish this, multi-wire detectors are being built to measure beam characteristics in the LEBT. More power is required for the RFQ cavity to deliver the desired higher intensity of protons. The debuncher will be implemented into the system. Power supplies currently being used for tests do not have the desired dynamic characteristics for the dynamic control needed to maintain the high acceleration efficiency throughout the cycle. This limitation may frustrate attempts to achieve the desired accelerated and extracted beam currents needed for the machine before it is shipped to Loma Linda.

Work on development and improvement of the accelerator will continue at Fermilab until the summer of 1989 when the accelerator will be disassembled and shipped for installation at Loma Linda.

The installation of the beam transport system and gantries will begin in June of 1989. It is expected that the installation of these systems will be completed and commissioning will begin by the end of 1989.

The building which houses the facility is three stories underground. It is a concrete structure which at this time is structurally complete and electrical, mechanical and finishing work is in progress. In addition to the below-ground structure there is a five-story hospital-type building which will be completed by the end of this calendar year.

Conclusion

The design and construction of the prototype accelerator is now complete. This greatly advances the opportunity to move proton therapy from the laboratories, where it has been so successfully implemented experimentally, to the clinical stage where this therapy may be instituted on a much larger scale for treatment of larger numbers of patients, with ever increasing application to other disease sites and for other diseases than have so far been attempted.

Further development and acceleration studies are now in progress at Fermilab and will continue after moving the accelerator to LLUMC next summer.

It is expected that this facility will begin patient treatments by the spring of 1990.

Acknowledgements

The authors wish to acknowledge the work of nearly 50 physics and engineering colleagues at Fermilab who have worked on component designs and fabrications which have greatly contributed to this project. Also the work of Accelerator Division engineers and technicians has been crucial to the start-up, commissioning and evaluation of performance of this accelerator. Our thanks to each and every one of them.

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