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THE FERMILAB NEUTRON RADIOTHERAPY FACILITY

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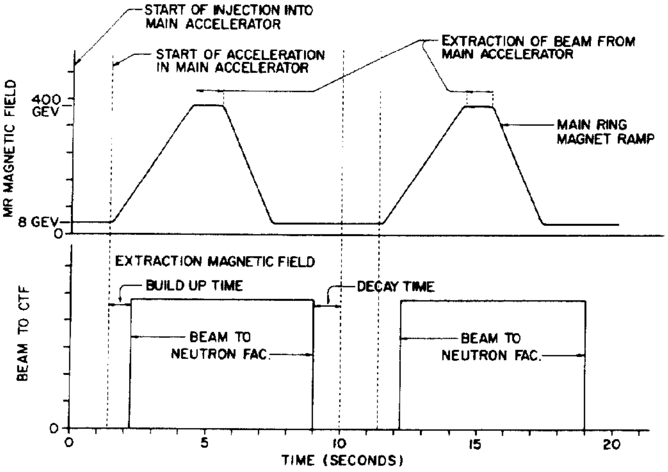
Introduction

A facility for testing the effectiveness of high energy neutrons for the treatment of malignant tumors has been constructed at the Fermi National Accelerator Laboratory.[1] The first neutrons were produced by the bombardment of 66-MeV protons on a beryllium target in July, 1975. After physically characterizing the neutron beam and performing preliminary radiobiological experiments, patient treatment started in September, 1976. At the time of this writing, 52 patients had been treated. A description of this facility is given below.

Compatability of Operations

The Fermilab linear accelerator[2] is used for its primary purpose of injecting 200-MeV protons into the higher energy synchrotrons for about one second out of every complete accelerator cycle. The accelerator cycle is determined by the main synchrotron. It can vary between seven and fifteen seconds depending upon its mode of operation. A typical 400-GeV magnet ramp with a one second flattop and a cycle time of ten seconds is shown in figure 1. Thus, the proton beam from the linear accelerator is available for secondary purposes between the one-second injection times. This is an appreciable fraction of the time for a typical accelerator cycle. The availability of this beam in the linac makes it possible to carry out a medical radiotherapy clinical program without appreciably interfering with the primary use of the Fermilab accelerator.



Beam Transport

Space considerations made it necessary to extract the proton beam from the straight section between tanks #4, and #5. At this point, the proton energy is 92 MeV. The space between tanks, however, is small and the conventional pulsed magnet with the greatest bending power that could be accommodated would only bend protons of about 65-70 MeV through the required angle. The proton energy after acceleration through the third cavity of the Fermilab linac is 66 MeV. These protons are allowed to drift through the fourth cavity without acceleration. The transverse focussing fields provided by the quadrupoles in the drift tubes of the fourth cavity keep the beam adequately focussed at this lower energy without additional tuning.

The proton beam is extracted from the linac by a pulsed C-type magnet placed between the linac cavities, which bends the beam through a 58° angle to miss the next cavity. A 32° d.c. H-magnet completes the 90° bend to send the proton beam through the ten-foot shield wall into the linac gallery. See figure 2.

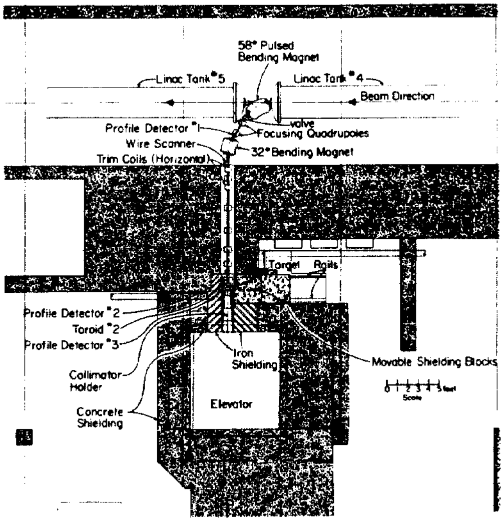


Figure 2

In addition to the two bending magnets, the transport line contains seven quadrupoles, steering dipoles, beam profile detectors, and beam intensity monitors. The beam-line has been tuned to give about 95 per cent transmission measured from the output of tank #4, to the vicinity of the target for the high intensity proton beam. The beam is focussed to a 5 mm diameter spot on a water-cooled beryllium target for the production of neutrons.

The compatible operation of the beam line to the medical facility between the injection times to the higher energy synchrotrons and the safety required in this facility have imposed stringent requirements on the control system. The control requirements have been met by the use of a two microprocessor system[3]. One is used for controlling the beam-line elements and reading the proton/neutron monitors, see figure 3, and one for controlling the medical treatment parameters. Communications exist between these two systems as well as to the linac control computer. Beam-line tune-up is done from the accelerator control room after which beam control is transferred to the local medical controls.

The Neutron Beam

Early in its development, a study[4] of neutron energy spectra, linear energy transfer distributions in tissue equivalent plastic[5], and dose rates was carried out using protons of 35 and 65 MeV and deuterons of 35 MeV incident on beryllium and lithium targets of various thicknesses. The results were qualitatively in agreement with theoretical expectations. In addition, they did not disclose any physical differences between the various beams which would make any one beam obviously biologically superior to another. Beryllium has technological advantages over lithium. Hence, it was selected for target material. A semi-thick target (2.21 cm) was chosen over a thick target because the dose rates were essentially the same, but the higher average neutron energy of the semi-thick target may have a slight advantage in skin sparing and dose attenuation length. A comparison of the neutron energy spectra due to 65 MeV protons incident on Be- is

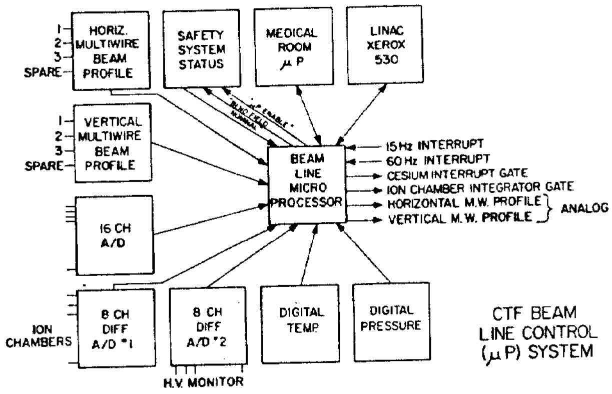


Figure 3

shown in figure 4, where A, B, C, and D refer to spectra due to target thicknesses of 2.41, 2.21, 1.96, and 1.60 cm, respectively.

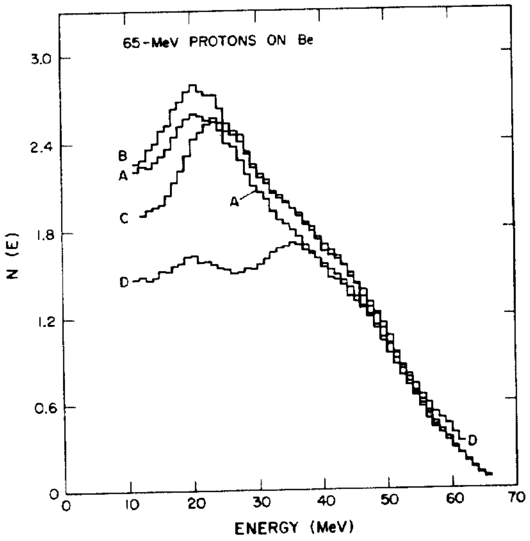


Figure 4

The neutron beam is collimated first by a 12.7 cm primary steel collimator, see figure 5. This collimator holds two ionization chambers which are used to monitor the neutron flux during experiments and patient treatment. These airfilled ionization chambers are made of aluminium with ceramic insulators. A thermocouple monitors their temperature. When corrected for temperature and atmospheric pressure, the output of these chambers referred to the output of a tissue equivalent ionization chamber mounted in a reproducible geometry remains within ±0.2% of an average value.

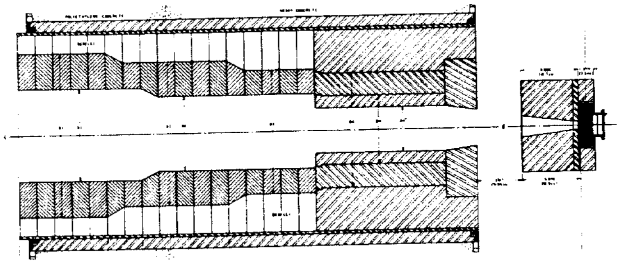


Figure 5

The beryllium target is housed in a water-cooled aluminum block. A gold disk is used to reduce neutron production and distribute heat for better heat transfer to the aluminum block.

Figure 6 shows results of dose rate measurements of neutron beams due to protons and deuterons of various energies incident on essentially thick beryllium targets.[4] The units are rad/min per microamp at 125 cm target-to-skin distance, versus energy of the incident beams.

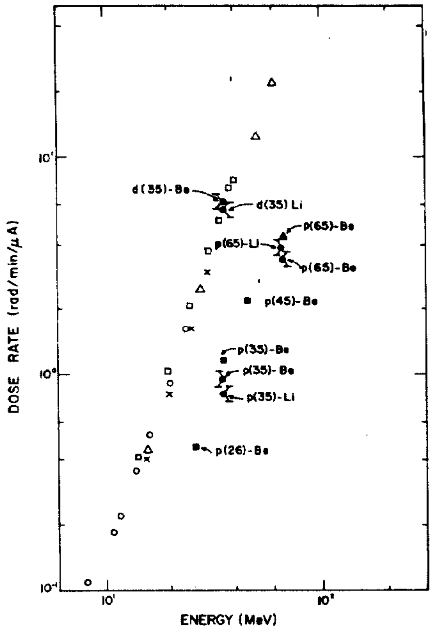


Figure 6

A typical dose distribution along the central axis of a 10 x 10 cm^2 neutron beam is shown in figure 7. The "skin" of the tissue equivalent solution-filled phantom was at 153 cm from the target.

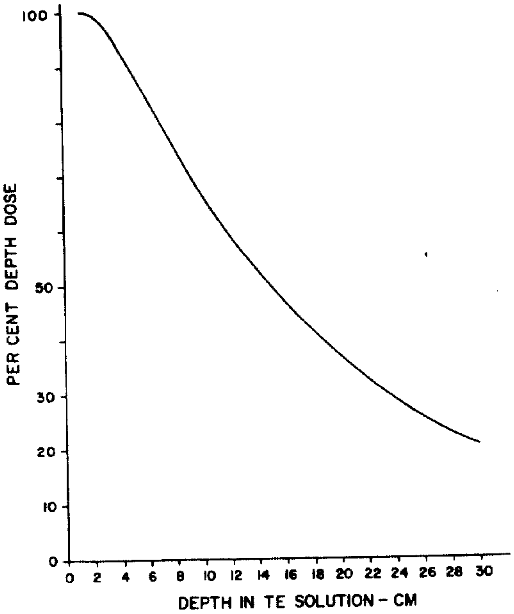


Figure 7

Figure 8 shows two beam profiles of this set-up taken at depths of 2 and 25 cm.

The neutron beam main collimators are cast with a mixture of polyethylene pellets, Portland cement, and water, in two series. One series, nicknamed "head and neck," allows the shaping of neutron beams up to

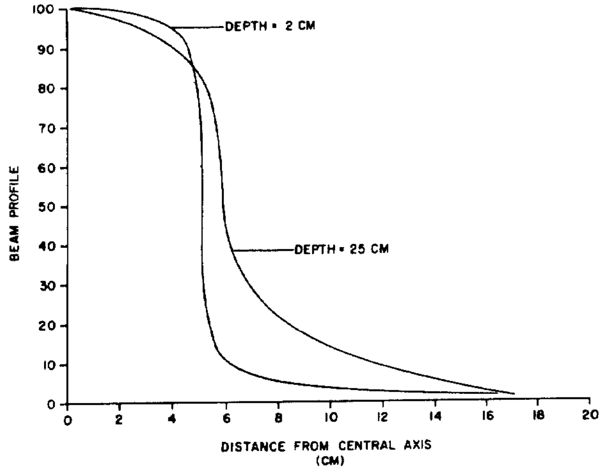


Figure 8

15 x 15 cm^2 (or 7 x 20 cm^2, etc.). The removal of a Benelex^R liner permits the insertion of larger collimators which may shape beams up to 30 x 30 cm^2. Using the liner alone as a collimator creates a clinically usable beam 24 cm in diameter.

The treatment room is built on a freight elevator. See figures 9 and 10. Entrance, simulation, and patient positioning take place at the upper level. A reference point, isocenter, is created by three orthogonal, horizontal laser beams.[6] This point is at the same distance from the X-Ray target, as the other isocenter point is at the neutron level. The lower isocenter is defined by four orthogonal, horizontal laser beams. The redundancy of laser beams as well as field lights make the work of the radiotherapy technologist much easier.

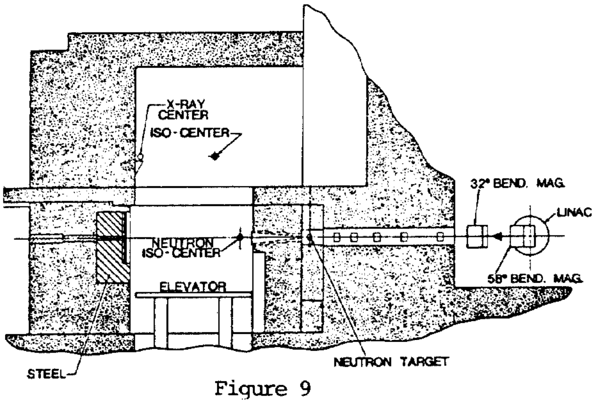


Figure 9

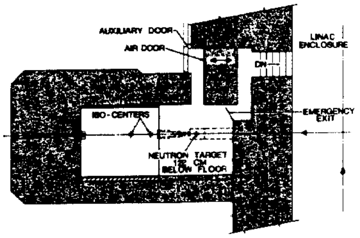


Figure 10

Medical facilities, a radiobiology and shop and a doctors' room and local control room are provided nearby. See figure 11.

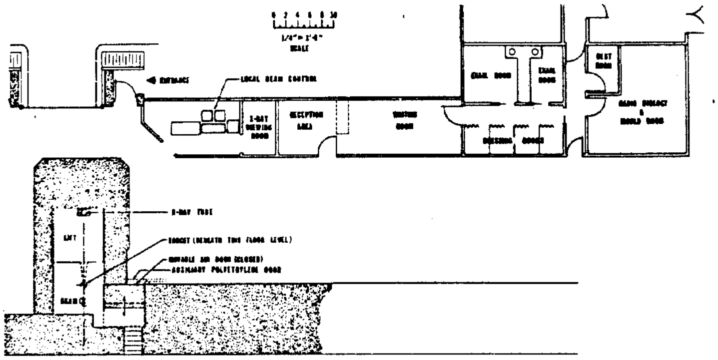


Figure 11

During the first seven months of operations, fifty-two patients were irradiated. Thirteen different radiotherapists have brought their patients and helped personally with examinations, simulations, and radiotherapy prescriptions. This underlines the fact that the Fermilab cancer therapy facility is a national resource available to all American institutions willing to participate in either the national or the special (local) cancer therapy research protocols.

This project is being supported in part by the National Cancer Institute, ERDA, and it has benefited greatly by contributions from the Illinois Cancer Council and the American Cancer Society, Illinois Division. Needless to say, the realization of this facility would have been impossible without the cooperation of a large number of dedicated workers from within and without Fermilab.

References

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