PROPOSAL FOR THE USE OF THE AGS LINAC FOR PROTON THERAPY*

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Abstract

The BNL 200 MeV linac presently provides beam for the AGS high energy physics program and for isotope production at the Brookhaven Linac Isotope Producer (BLIP) facility. There is now a proposal to develop a proton therapy facility which would also use the linac beam. Approximately 1% of the current in each linac beam pulse would be diverted from BLIP, down an existing transport line, to the proposed new facility. This paper focuses on the basic design of the facility, particularly the accelerator issues. The planned transport line layout is presented, along with a description of the energy and intensity control, and beam delivery systems. In the initial phase, we are planning one 360° vertical gantry and one horizontal treatment room.

Introduction

In the AGS linac, H^- ions are accelerated to 200 MeV in 25 mA, 500 μs pulses, at a repetition rate of 5 Hz. Approximately 4 pulses every 3.8 seconds are delivered to the AGS Booster for high energy physics, with the remaining pulses going to BLIP [1], a facility that produces radioisotopes for use in medical diagnosis and therapy. An upgrade of the linac is presently in progress which will result in a higher average beam current being delivered to BLIP. Following completion of the upgrade in 1996, 30 mA, 650 μs pulses will be accelerated at a 7.5 Hz rep rate, giving an average linac current of 146 μA (9 x 10^{14} H^-/second). In addition, reliability of the linac should be improved as a result of this upgrade. There is a high probability that the linac will subsequently be funded to operate a larger fraction of the year (possibly up to 46 weeks per year, vs. the present 25-30 week period). This has made it attractive for us to consider the possibility of also using the linac for proton therapy, in a way which would essentially be transparent to the BLIP and AGS operations. In addition, there already exists a 200 MeV transport line as a spur from the BLIP line, which takes the beam to what had been the Radiation Effects Facility (REF), and the Neutral Beam Test Facility (NBTF), both no longer in operation and potentially available for this application.

Figure 1 shows the layout of the existing and proposed facilities. A pulsed dipole magnet switches beam pulses between the AGS Booster injection line and BLIP. The REF/NBTF line branches off the BLIP line, and there is a 116 m transport line, including three 30 degree dipoles, before the beam enters the NBTF experimental hall. The dipoles, quadrupoles, power supplies, and vacuum system are already in place for this transport line, but some additional elements will be added to better meet the needs of the therapy facility. The NBTF experimental hall, with a floor space of 9.1 m x 24.4 m, will be converted into a horizontal beam patient treatment room. A new beamline will be added off of the NBTF transport line to deliver beam to a 360° gantry, in a new room. The remainder of the NBTF facility will be converted to offices, patient examination rooms, reception and waiting areas, etc. There is sufficient space to expand the facility for additional horizontal and gantry rooms in the future. The REF experimental hall, also shown in Fig. 1, could be used for beam characterization, detector development, and development of scanning system.

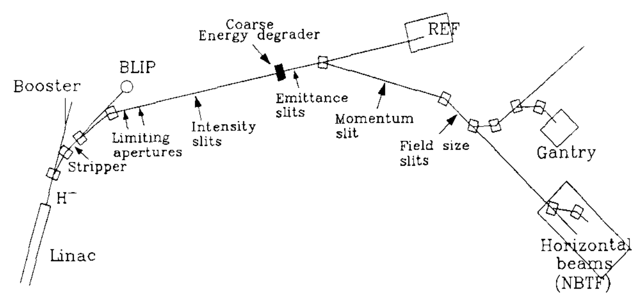

Fig. 1. Schematic of transport lines to therapy facility.

General Design Features

We initially considered sending a certain number of the linac pulses to the therapy facility, but one could easily imagine that future demands for beam for therapy would not be met without taking an excessive number of pulses from BLIP. We have therefore decided to take a small fraction of the current (1%) in every pulse delivered to BLIP, and divert it to the therapy beamline. As will be described below, this is easily done since the linac accelerates H^- ions. Since BLIP essentially always requires 200 MeV beam, with this scheme the proton therapy energy must be controlled downstream of the BLIP line.

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Almost the full linac energy of 200 MeV would be required to treat deep tumors in larger patients. Therefore, our design minimizes the loss of beam energy in the beam-spreading and beam-flattening process. "Voxel-by voxel" treatment, while preserving the full beam energy, would lead to treatment times which are too long for medium and large tumors at the 7.5 Hz repetition rate of our linac. Therefore, in order to lose less energy than a conventional double scattering beam-spreading system, we have chosen to replace the first scatterer with spreading via quadrupole magnets. This would be followed by either an occluding ring [2] or contoured scatterer [3] for flattening of the distribution. (A scanning system with a ribbon beam could be implemented at a later time).

Bragg peak spreading can not be done easily during a 650 μs beam pulse, so we will treat the full field first at one depth, and then change the beam energy. Energy modulation will be carried out in two steps - a coarse energy degrader, shown in Fig. 1, located approximately 84 m upstream of the treatment room, and a fine energy degrader, for Bragg peak spreading, located close to the patient.

Collimators downstream of the coarse degrader will be used to produce a beam of small emittance and small energy spread before reaching the beam delivery sections. The beam intensity will be adjusted so that at least 100 pulses are required to treat the distal edge of the tumor. The intensity could then remain the same throughout the treatment, and the number of beam pulses would be controlled to give the desired dose at each range. The fine energy degrader would then be changed for the next energy step. With this scheme, each beam pulse contains no more than 1% of the dose required at a given depth. Total treatment times should be approximately 60 seconds, assuming it takes 1 s to make an energy change with the fine degrader.

Beam Splitting From BLIP

The BLIP beamline will require minor modifications to allow 1% of the beam in every BLIP pulse to be directed to the proton therapy facility. A thin carbon button, suspended in the beam using 5 micron graphite fibers, will be placed just upstream of an already existing dipole magnet. The 1% of the BLIP beam which passes through this stripper is converted to H^+, and in the dipole following this stripper it is deflected 3.75° to the REF/NBTF beamline, while the remaining 99% H^- beam is deflected 3.75° to BLIP. This configuration is failsafe in that the stripper breaking/falling would result in no beam to PTF.

Transport to the Coarse Energy Degrader

The H^+ beam is transported 49 m to the coarse energy degrader, with two bends in the line forming an achromat. At two places in this section, there are fixed limiting apertures which would serve to stop any beam originating from other than the stripping button.

There is a 10 m drift in this line where the beam is 1 cm diameter. Although not shown in Fig. 1, three small dipoles put a bump in the orbit 8 cm off axis in this section - the first magnet gives the beam a 10 mrad kick; the second magnet, 8 m away, kicks the beam 50 mrad back to the centerline; the third dipole, 2 m further downstream, puts the beam back on axis. The second and third dipoles are dc magnets, while the first is a pulsed magnet (laminated or ferrite). When one wishes to turn off the beam, this first dipole can be turned off quickly and the beam is stopped in a beam dump.

Coarse Energy Degrader

We have chosen to do the coarse energy degradation far upstream of the patient, since the intensity is sufficient to allow the use of collimators downstream of the degrader to produce a beam of small emittance and energy spread before reaching the beam delivery sections. This has the advantage of reducing the energy degradation required near the patient, where transverse momentum spread, fast neutrons, and gammas can be a problem. Initially, for simplicity we plan to have the coarse energy degrader give one of four energies, 200, 160, 120, or 80 MeV. (It will be a simple matter to expand the choice of energies in the future, and ultimately one can degrade the energy at this upstream location to match the distal edge of a tumor.)

Emittance and Momentum Slits

An aperture at the degrader exit, and a second aperture 2 m downstream, will define the exit beam position, size, and angular spread, (i.e., emittance). These will be set to provide a beam with a transverse emittance of 20 π mm mrad (unnormalized). A 0.6 mm thick lead foil located in the energy degrader will be used with the 200 MeV beam, so that full-energy beam will also pick up some extra divergence, while losing only 0.2 MeV in energy. (That is, the emittance of the 200 MeV beam is first increased, and then recollimated to 20 π mm mrad).

After a 30° bend, a horizontal collimator at the image point of the exit aperture of the degrader (and the maximum dispersion point) will serve as a spectrometer to produce a well defined beam energy, as well as to limit the momentum spread of the beam to that required to contribute $<$ 2 mm range error (or alternatively 1% maximum dp/p). The beam energy will be independently verified as part of the safety systems, using downstream magnets.

Intensity Control

In the above sections, we have chosen to take 1% of the current in each BLIP pulse for PTF, have limited the emittance entering the beam delivery section to 20

π mm mrad, and have limited the momentum spread to give < 2 mm range error (or 1% dp/p maximum). With these boundary conditions, the maximum intensity which can be delivered to the beam delivery section varies from approximately 10^{12} protons/sec at 200 MeV to approximately 10^{10} protons/sec at 80 MeV. The lower intensity at lower energy is generally acceptable, since the beam range is smaller. More pulses can thus be used at a given range since fewer energy steps would be required, and treatment times remain reasonable. The intensity can be reduced below these maximum values without changing the other beam characteristics by using a set of collimating slits located before the coarse energy degrader. Alternatively, one could reduce the intensity using the momentum slits described in the previous section.

Field Size Control

Both the gantry and horizontal beam delivery systems, described below, are designed to transport the beam of 20 π mm mrad into a field of up to 30 cm diameter at the patient, using quadrupole magnets to spread, and an occluding ring or contoured scatterer to flatten the beam profile. A set of horizontal and vertical collimators in the transport line, downstream of the momentum slit, can be used to reduce the transverse emittance of the beam (unnormalized), to below 20 π mm mrad in each plane. The location of these slits has been chosen such that the reduction in emittance results in a reduction in the field size at the patient, with all elements in the beam delivery system remaining the same. These slits can thus be used to reduce the field size to match the desired treatment. The field size could also be adjusted using the spreading magnets. A multileaf collimator will always be used in addition, for shaping the radiation field proximal to the tumor.

Beam Delivery

One beamline in the horizontal treatment room will produce up to a 30 cm diameter field, and will have a patient table, as well as a chair for head and neck treatments. A second beamline in this room will be dedicated to eye treatments. In selecting the best gantry design, there are tradeoffs to consider in room size, gantry weight, power requirements, simplicity of beam optics, etc, and we are still studying all alternatives. In one preliminary design, we propose spreading the beam magnetically to a 30 cm diameter field, with a distance of $\approx$ 3 m from the last magnet to isocenter.

Conclusions

We have a design which allows the use of the 200 MeV linac beam for proton therapy, with minimal impact on the high energy physics and isotope production programs. Much of the required beam transport system already exists. The transport line from the linac to the energy degrader always remains at fixed settings, with the exception of slits to control the beam intensity. From the coarse energy degrader through the beam delivery section, one has only to choose one of four sets of magnet settings, for the four operating energies. The entire beam transport, from the linac to the exit of the gantry or horizontal line, can remain fixed for a full treatment (one field). The beam intensity can be changed without changes in the beam optics, and the field size at the patient can be changed without any magnet changes. With the linac rep rate of only 7.5 Hz, treatment times will be on the order of 1 minute.

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