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DESIGN OF A BEAM TRANSPORT SYSTEM FOR A PROTON RADIATION THERAPY FACILITY

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Abstract

A new beam transport system has been designed to bring the 210 MeV proton beam from the Indiana University Cyclotron to four proton therapy treatment rooms. The main trunk line will be achromatic and employ a fast beam splitting system to allow treatments simultaneously in different treatment areas. To enhance flexibility of operation, each treatment room will have its own energy degrader and energy selection system. There will be two treatment rooms with a fixed horizontal beam line. The first will be an upgrade to our current eye treatment facility and the second will be designed for head, neck, and brain treatments including stereotactic radiosurgery. In addition, there will be two rooms with iso-centric gantries for more complex multi-port treatments.

1 INTRODUCTION

The Indiana University Cyclotron Facility (”IUCF”) is planning a conversion of the space formerly used for nuclear physics experiments into treatment rooms for proton radiation therapy treatments under the auspices of the Midwest Proton Radiation Institute (”MPRI”), an organization being developed by IUCF in conjunction with the Advanced Research Technology Institute (”ARTI”) at Indiana University [1]. The 210 MeV cyclotron at IUCF will be used to provide protons to the treatment rooms. In addition there will be an experimental room for biological and radiation effects studies. This paper will describe the beam transport system being planned for this facility.

2 BEAM LINE OVERVIEW

The beam line has been designed to provide beams of easily adjusted energy and intensity to each of the treatment rooms in time slices on the order of hundreds of milliseconds. A portion of the full energy beam will be carried to a remote beam dump to aid in the control and stabilization of the cyclotron beam. The emittance of the full energy beam from the cyclotron is small (≤ 3 π mm-mr). The energy degradation process significantly increases the beam emittance and the energy selection systems and gantries have been designed with an acceptance of 30 π mm-mr representing a compromise between intensity loss and magnet size and cost. The design has focussed on minimizing the number of new magnet designs and will use existing IUCF magnets wherever that is consistent with the clinical design requirements. The layout of the beam line is illustrated in Fig. 1.

2.1 Beam Achromat Section

Currently the cyclotron beam passes through a 45° dipole magnet and enters a beam corridor which leads to several experimental rooms. The current beam line has a large momentum dispersion to meet the nuclear physics experimental conditions. This initial section has been redesigned with the addition of a pair of opposed 30° dipoles. This section then can be tuned so that both spatial and angular momentum dispersions of the beam will be zero everywhere in the trunk line leading to the treatment rooms. This ion-optical condition reduces horizontal beam instabilities due to movements caused by momentum changes of the cyclotron beam.

2.2 Beam Trunk Line and Splitting Systems

Each treatment room will have its own local energy degrader system and as a consequence the trunk line will operate at a fixed energy and existing quadrupole magnets with solid iron returns can be used. The cyclotron beam with a maximum intensity of about 1.0 μA will be transported the length of the trunk beam line into the main beam dump at the end of the system. Distribution of beam into the five rooms, R1-R5, will be done using a fast beam splitting system at the entrance to each room.

The splitter system to be used will be a modified (and simplified) version of those currently used in routine operations for the IUCF beam lines. Each splitting system will consist of a fast kicker dipole with a rise time of about 1 ms and a Lambertson septum magnet and will be installed in the drift space in the trunk line at the entrance to each area. When no beam is being requested from a treatment area the full beam will be transported down the trunk beam line into the main beam dump. When one treatment room requests beam, the appropriate kicker dipole will be activated for the duration of the request and beam will be kicked down into the Lambertson dipole gap and bent 12° horizontally into the energy selection system of the treatment room.

The present proposal is to have a 4 Hz cycle divided into four packets: treatment slot A (100 ms), treatment slot B (100 ms), radiation research (25 ms), and beam diagnostics (25 ms). Each time slot will be reserved for their dedicated purpose. The first treatment room to request beam will have the 100 ms of treatment slot A reserved for their sole use. If a reduced dose rate is required, the time slot can be reduced to a minimum of about 10 ms (set by the magnet rise and fall times). Further beam intensity reduction can be accomplished by the beam intensity modulation systems presently in use at the cyclotron. This consists of electrostatic quadrupoles in the low energy beam lines and allows modulation of the beam intensity on a time scale faster than

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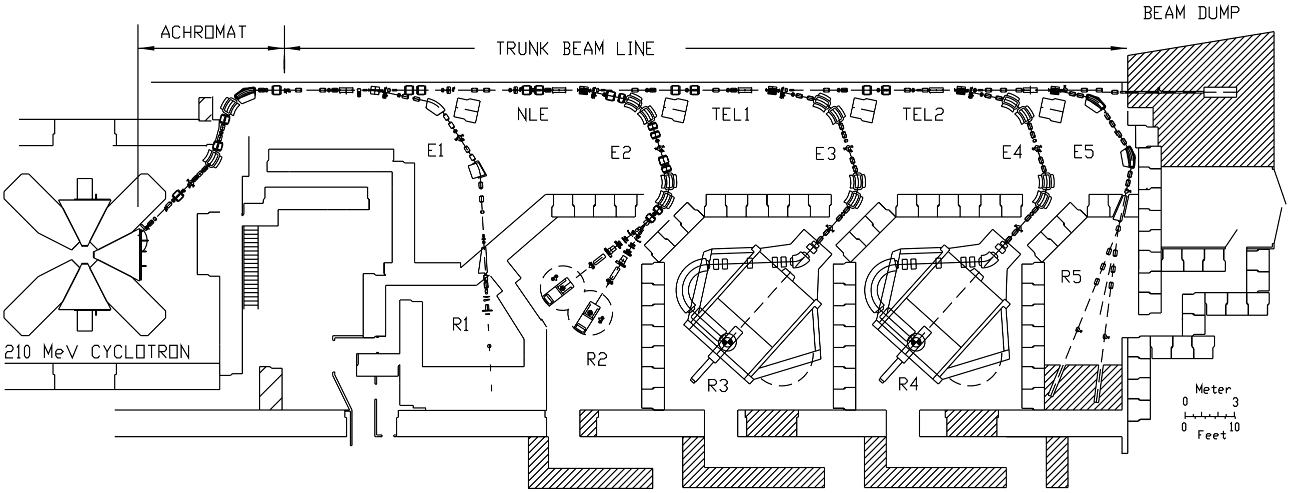

Figure 1: Layout of beam transport system and treatment rooms for the Midwest Proton Radiation Institute

the 1 ms of the splitter system. A second treatment room can independently request beam during time slot B of the 4 Hz cycle.

2.3 Non-Linear Expansion Section

For medical treatment the dose uniformity has to be constant to about ± 2% over the treatment region. Cyclotron beams do not meet this requirement and beam spreading systems are necessary to prepare a usable beam distribution. The double scattering beam spreading system has the disadvantage of reducing the beam energy. Therefore the primary beam needs to have a significantly higher energy than that required at the treatment location.

Another technique for generating large area uniform beam distributions is using multipole magnets to alter the beam phase space as described by [2],[3], and [4]. Their designs provide for uniform beam distributions over areas of several hundred square centimeters using only static magnetic elements. This feature would provide significant advantages in terms of control, diagnostics, and operational flexibility in a radiation therapy setting. The section of beam line (NLE) between the first two splitters has been designed to allow for the possibility of incorporating such a system, by inserting multipole magnets at two locations: one where there is a horizontal waist and a large vertical beam width and a second where the horizontal and vertical conditions are interchanged. A preliminary design study of a non-linear expansion system has been done [5] to determine whether such a system is feasible using our energy selection systems and basic beam line design. At this point, it appears to be feasible to incorporate such a system in our design. The beam telescope systems after each splitter magnet do not change the modified phase space properties and allow a large area beam to be delivered to each treatment area if desired. What remains to be done is the determination of multipole requirements needed to match to both our energy selection system as it has evolved and the isocentric gantries when their design is complete. Development efforts will also be required to guarantee meeting clinical dosage uniformity specifications.

2.4 Energy Selection System

Energy selection systems (E1-E5) will be installed after each kicker/Lambertson magnet combination at the entrance to each treatment room. The 210 MeV proton beam will pass through a degrader appropriate to the treatment energy and then enter the momentum analysis system. The fixed horizontal line and the two gantries (E2, E3, and E4) require fast and reproducible energy changes and so will be equipped with an achromatic energy selection system using laminated magnets. Since the modified eye line (E1) will operate at a fixed energy it will use existing solid iron magnets. Similarly, the research and radiation effects line (E5) will utilize existing magnets since it does not require rapid energy changes.

The energy selection systems (E2, E3, and E4) for the three new treatment rooms (R2, R3, and R4) will be identical. A variable thickness degrader will be followed by a magnet system consisting of four 30° dipole magnets and eight quadrupole magnets (QQDDQQQQDDQQ). A horizontal slit system in the center of the system will provide momentum analysis of the beam. The resolving power of the system $p/\Delta p$ = R16/($2x_0$*R11) = 420 for a horizontal object size of $2x_0$ = 3 mm at the degrader, which provides a maximum energy spread of less than ± 0.5 MeV at 210 MeV. This resolving power is necessary to meet the medical distal fall-off requirement. The system will deliver an achromatic beam at the entrance to the gantries and the fixed beam line nozzles. The beam will be at a double waist (vertically and horizontally identical) at those locations.

2.5 Beam Telescopic Sections

The beam line sections (TEL1 and TEL2) connecting the splitter magnets leading to treatment rooms R2 and R3, and connecting the magnets leading to rooms R3 and R4, have been designed to have unit transfer matrices so that the beam properties at the entrance to each of the energy selection systems will be identical and the three new energy selection systems will be identical.

3 TREATMENT ROOMS

The layout of the facility shows four treatment rooms R1 ... R4 and one experimental area R5 for biological and radiation effects studies. The first treatment area R1 closest to the cyclotron is a fixed horizontal beam designed for eye treatment. This area is already in operation and presently used for a study of age-related macular degeneration.

The second treatment room R2 accommodates two fixed beam lines which will be configured for head, neck and brain treatments. Also stereotactic radiosurgery will be possible in this room. For more complex treatments both treatment areas R3 and R4 will be equipped with isocentric gantries.

For optimal use of the beam of the cyclotron another room R5 at the end of the existing building will allow radiation effects in two fixed beam lines. Also biological studies will be possible in this room.

3.1 Beam Spreading Systems

In order to carry out large area irradiations, the beam line has been designed to be compatible with double scattering systems, magnetic wobbling systems, and eventually with a full three dimensional scanning system. The double scattering system is simplest and will be used wherever the limits imposed by additional energy and flux loss allow. Magnetic wobblers eliminate those problems but add some complexities in both dosage control and verification. However, those problems will require solution in order to develop a system capable of providing three dimensional intensity modulated treatments. It is also hoped that the static non-linear expansion system described earlier can be developed to provide irradiations with clinically acceptable uniformity.

3.2 Preliminary Gantry Design

We have concluded that a single plane gantry will better satisfy our requirements than either a corkscrew gantry [6] or a gantry of the type in use at PSI [7].

A single plane gantry consists of two dipole magnets which bend the beam first 45° away from the beam axis and 135° back to the isocenter, perpendicular to the original beam direction. Five entrance quadrupoles and five quadrupoles between the dipoles are needed to guide the beam of 30 π mm-mr emittance in both transverse directions through the narrow dipole gaps and to meet achromaticity and other beam requirements at the isocenter. Since the gantry will be used at arbitrary azimuthal angles it is important to provide an achromatic beam with identical emittances at the gantry entrance. The beam at the exit of the energy selection systems meets those requirements and is further shaped by the entrance quadrupoles to meet the aperture restrictions of the gantries.

A single plane gantry is presently commercially available [8] and has been schematically shown in figure 1 with the addition of a fifth entrance quadrupole which improves the matching to our energy selection system.

4 MAGNET DESIGN

The new beam line requires the design of a new 30° dipole magnet. Two of these laminated magnets will be used in the beam achromat section preparing the beam for the trunk line and four of the dipoles will be used in each of the energy selection systems. No new quadrupole magnet designs will be required. Either existing beam line quadrupoles will be used (in the trunk line) or copies of one of the two types of quadrupoles used in IUCF's electron-cooled storage ring will be used. These laminated quadrupoles will be used in the energy selection systems and at a few locations in the trunk line where stronger fields or larger apertures (10 cm diameter) are required.

5 REFERENCES

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