DESIGN AND CONSTRUCTION PROGRESS ON THE IUCF MIDWEST PROTON RADIATION INSTITUTE

D.L. Friesel, V. Anferov, B. Broderick, J. Collins, V. Derenchuk, G. East, D. Jenner, W.P. Jones, J. Katuin, S. Klein, J. Self, W. Starks, N. Schreuder, IUCF, Bloomington, IN 47408, USA

Abstract

Construction of the IUCF Proton Therapy Cancer Treatment facility, the Midwest Proton Radiation Institute (MPRI), has been underway for two years. Upgrades to the IUCF separated sector cyclotrons, including a 750 keV proton RFQ pre-injector system, are nearly complete. The medical beam transport system consists of a 205 MeV proton "Trunk" beam line and three energy selection beam lines (ES lines). The trunk line is complete and has been partially commissioned. The first ES line has been installed and commissioning is underway. The MPRI beam delivery system is unique in that 205 MeV protons can be rapidly switched (3ms switch time) from the "Trunk" into each of the three planned ES lines, where the proton energy delivered to each treatment room can be independently degraded to as low as 65 MeV.

Construction and installation of the beam delivery (nozzles, diagnostics, wobbler, etc) and patient positioning hardware (based on industrial robot technology) in the first treatment room are in progress and commissioning will begin in the last quarter of 2002. Installation of a 360 degree rotating gantry system in the second treatment room will be completed by the end of 2004. This contribution will present the unique beam delivery features of this new proton therapy facility and review the present status of the project

1 FACILITY DESCRIPTION

The Indiana University Cyclotron Facility (IUCF) houses two separate accelerator systems for research and applications. The first is a synchrotron based nuclear physics research facility made up of an intense (~1 mA peak) polarized proton and deuteron ion source (CIPIOS) [1], a 2.4 Tm booster synchrotron (CIS) [2] and a 3.6 Tm electron cooled synchrotron storage ring (Cooler) [3]. The second system consists of a K15 separated sector injector cyclotron and a K220 separated sector main cyclotron [4]. Previous papers [5] have described the scope of the project to convert the cyclotron-based nuclear physics research areas to use as a medical facility for proton radiation therapy. The floor space previously used for nuclear physics and applied research with beams accelerated by the coupled cyclotrons have been reconfigured to provide space for three proton therapy treatment rooms. The first treatment room will contain two horizontal treatment beam lines: a small field (eye line) (5-30mm diameter) and a large field line (adjustable from 20 to 200 mm diameter). The second and third treatment rooms will each house a 360 degree rotating gantry.

2 UPGRADES AND OPERATIONS

A historical review of the reliability and performance limitations of the IUCF cyclotrons revealed several areas where improvements could significantly enhance their effectiveness as a proton source for Cancer Therapy. In their historical use as nuclear physics research tools, the cyclotrons accelerated a variety of particle species to a wide range of final energies dependent on the nuclear physics requirements. Designing a variable-energy multi particle cyclotron requires that a large number of compromises be made. Switching to a mode of operation as a fixed energy proton accelerator has given us the opportunity to review those compromises and optimize many designs specifically for 205 MeV operation. Beam energy variability will be accomplished with an energy degrader at the entrance of the beam transport lines to each of the three planned treatment rooms to permit rapid setup and delivery of proton beams between 65 and 205 MeV to each treatment room. In addition to optimizations for operations, systems causing significant downtime were identified and are being replaced or upgraded.

The 600 kV ion source terminal experienced voltage holding and regulation problems, and will be replaced in August, 2002 with a commercial 750 keV Radio Frequency Quadrupole (RFQ) pre-injector. A 20 keV proton beam will be generated by a 2.45 GHz microwave driven ion source. This source has been designed to be very reliable and require minimal maintenance. Only the source body will be elevated to 20 kV eliminating the need for a high voltage rack. Over 1mA of the 20 keV beam will be transported through a 1.5 meter long beam line containing a 17.75 MHz (1/2 the fundamental cyclotron frequency) chopper and beam intensity modulation system and focused into the RFQ with a magnetic solenoid lens. The design for the new 750 keV RFQ and low energy beam transport system was provided by AccSys Technology, Inc [6] and were previously reported [7]. It has a 120 cm long accelerating structure which operates at 213 MHz (six times the fundamental cyclotron frequency). The 20 keV beam will be accelerated to 750 keV and transported 113 cm to the center of the K15 cyclotron where it will be inflected onto the first turn of the cyclotron.

A new cyclotron control computer and V-system software package were installed and commissioned in March 2001. New controls hardware (DAC/ADC/PLC) was installed in early 2002, and are similar in design to the systems developed for the 2.4 Tm CIS booster synchrotron commissioned in 1998 and more recently installed on the "Cooler" in 2000 [8]. These new cyclotron controls are the first part of a more global MPRI treatment control system.

Other cyclotron system upgrades include re-alignment of the main cyclotron extraction system, re-tuning both cyclotron rf amplifiers for peak operation at 35.58 MHz (205 MeV protons) and operation with dee voltages of 50kV and 200kV respectively, replacement of all cyclotron and beam line de-ionized water cooling systems, and the addition of new beam diagnostic devices (BPM's, wire HARPS and scanners, phase probes) to aid in the set-up and monitoring of beams for proton therapy. These and other smaller upgrades are designed to provide the 95% beam delivery reliability specified for MPRI operations.

3 MPRI BEAM DELIVERY SYSTEMS

Construction of the MPRI beam delivery system began with the installation of a 14.3 m long achromatic beam line at the exit of the main cyclotron. This will feed a 57 m long "Trunk Line" which ends at a beam dump at the north end of the cyclotron hall. The doubly achromatic waist at the end of the Achromat is reproduced near the entrance to each of the three energy selection beam lines (ES1, 2, & 3). Since the cyclotron will be operated at a fixed energy of 205 MeV, the achromat and trunk beam lines are constructed using non-laminated quadrupole and dipole magnets recovered from the original cyclotron beam lines. The trunk line beam dump will house a multi-layer Faraday cup [9] to continuously monitor the cyclotron beam energy with a resolution of about 100 keV.

Three beam splitting systems, each consisting of a fast ferrite kicker and Lambertson dipole magnet [10], are used to switch 205 MeV protons from the trunk into each of the ES lines on demand. A variable thickness energy degrader will be located at an achromatic double waist (in order to minimize emittance growth) immediately following the Lambertson dipole in each ES line to vary the proton beam energy between 205 to 65 MeV. Consequently, the ES lines are constructed using laminated dipole and quadrupole elements to facilitate rapid energy changes during clinical operations. In order to match any possible future cyclotron upgrade, all Beam Delivery System components have been designed to operate at energies as high as 235 MeV. The energy degrading process increases spatial, angular and energy spreads in the therapeutic beam. It also creates a significant flux of secondary neutrons. The ES beam line based on two bending magnets will prevent secondary neutrons from entering the treatment room, while delivering a doubly achromatic beam to the entrance of each treatment room. The momentum selection slit together with Multi-Leaf Faraday Cup will be installed in the middle of the ES line to select and verify the energy and energy spread of the degraded beam. Two radiation safety beam stops behind the slits will prevent the beam from entering the treatment room until the energy verification is complete and treatment room is ready to start the treatment. The Secondary-electron Emission monitor and Gas Harp will monitor the beam current and the beam spot size and position at the entrance to the Nozzle. The beam splitting, energy degrading and ES transport systems permit the simultaneous delivery of pulsed beam to each treatment room with its own energy, intensity and distribution. This is essentially equivalent to having a cyclotron for each treatment room.

Beam diagnostics in the MPRI beam delivery systems include non-destructive beam position and intensity monitors (BPM's), multi-wire Harps and wire scanners for beam intensity and position measurement, and multi-leaf Faraday cups and time-of-flight (TOF) devices for energy measurement. Feedback hardware and software will be used to automatically keep the beam steered through the center of the trunk line to the beam dump. A TOF monitor in the trunk line Achromat and the multi-layer Faraday cup in the trunk line beam dump and ES line will be used to set up and maintain a constant energy beam in the ES lines during treatment. All beam splitting, diagnostic, and feedback systems have been developed and used at IUCF during the previous 25 years of operations for nuclear research.

The Achromat line was commissioned in November, 2000 [11]. Installation of the trunk line, beam dump and delivery of 205 MeV protons to a temporary Radiation Effects target station just in front of the beam dump was completed by December of 2001. Phase I construction plans call for the completion of the ES1 line and the fixed horizontal beam treatment room and clinical facilities in 2003, and the ES2 beam line and Gantry room in late 2004. The ES1 beam line has been installed during March-April 2002 cyclotron shutdown. All components have been successfully tested off line prior to the installation. Using the 205 MeV beam we performed the magnet alignment test, which verified correct installation of the magnetic elements. Next, we plan to verify ion-optical properties of the beam line, which will include tests for achromatic beam properties at the entrance to the treatment nozzle.

4 TREATMENT ROOM FACILITIES

The MPRI fixed Beam treatment room contains two beam-lines: One for high energy and larger field treatments and one beam-line for small fields and lower energy treatments such as for eye treatments. The latter is referred to as the eye-line. Both beam-lines are fixed and horizontal. Beam wobbling will be used in the large field line, and the wobbler magnet design has been finalized and construction of the magnet underway. A ±10 degree switch magnet is used to switch the beam between the two beam-lines. The design of the switch magnet is complete and fabrication underway. The civil construction of the Fixed Beam line treatment room is currently underway. This includes the installation of all the services and utilities, the raised floor and dry walling as well as all the interior decorating. An outside company has been contracted to do this together with the rest of the clinic. The completion date for the treatment room is August 1, 2002. The nozzle support structure, the mounting posts for the x-ray sources and alignment devices and the support ring for the rotating floor assembly have been installed and aligned prior to this major construction effort.

Once this construction phase has been completed the installation of the nozzle components for both the large field and the eye lines, the x-ray system as well as the patient positioner will commence. The Room and Dose Delivery Control systems, including the beam spreading system, will be installed during September and October. This will allow the medical physics team to start beam-commissioning tests in November when the cyclotron becomes available again i.e. after the RFQ injector has been installed. This will include finding the appropriate raster or wobbling scan patterns to spread the beam and designing ridge filters to modulate the beam energy to obtain the required Spread out Bragg Peaks (SOBPs). Selecting the appropriate energy and momentum band in a reproducible and accurate manner in the energy selection line is also important process, which is essential to obtain the reproducible beam parameters on a daily basis. All this needs to be completed by January 2003 to allow measuring the beam data to be installed in the treatment planning system prior to March 2003.

The design and development tasks to achieve the above mentioned goals are currently progressing according to schedule and it is therefore realistic to expect the treatment room to be ready to treat the first patients in 2003.

The second treatment room to become operational will contain a 360^o rotating gantry. Two 40'x29'x12' deep concrete lined pits have been dug into the floor of the IUCF cyclotron experimental hall to house the gantry support structures. These are large enough to house most known commercially available gantry designs. Formal requests for price quotations for a commercial gantry structure and beam transport system are being processed, with the intent to purchase the first gantry by early fall of 2002. A 30 ton bridge crane is available in the cyclotron hall, and covers the location of the gantry pit. IUCF and MPRI may elect to fabricate the gantry beam transport system and nozzle in-house.

A commercial Motoman UP200 robot is being adapted to precisely position patients in both MPRI treatment rooms. Commercial robots are relatively inexpensive, are engineered with excellent precision, and have an extensively documented operational history. The MPRI patient positioning system will utilize three independent technologies to assure patient safety and/or position accuracy. The robot will translate the patient from a docking station to a predetermined location in the beam coordinate system. An optical tracking system will follow the robot movement and provide a collision safety mechanism. Digital radiography will be used to verify the accurate location of the biological target at the beam iso-center, and direct any fine adjustments required to match the treatment prescription. In addition, the robot will be fitted with accelerometers and inclinometers to further verify the internal robot guidance system readout and assure the safety of the patient. The robot has been delivered and development of it and the associated Robot Interface and Position Verification System (RIPVS) is currently proceeding in a temporary location. When the construction in Treatment Room 1 is completed later this summer, the robot, optical tracking system and RIPVS will be moved into their permanent location.

5 MEDICAL FACILITY DEVELOPMENT

Medical facilities are being constructed to provide support for the clinical application of the cyclotrons. The clinic will be housed largely within the existing structure, making use of the areas previously occupied by nuclear physics experimental stations and the "low bay" research support area. The layout is based upon a wheel and hub configuration that allows the staff to be centrally located. The floor in the clinic area will be raised approximately two feet above the existing concrete floor to allow conduit, ductwork, plumbing and cable accessibility, ease of access to the beam line in the treatment rooms, and increased cushioning to reduce job related fatigue. Patients will enter MPRI by way of a new parking lot, lobby and reception area to be constructed at the north end of the building. IUCF staff will continue to use the parking facilities and entrance on the east side, upper level, facilitating the ease of operations of all IUCF supported activities. Construction of the clinical facilities began in early May 2002 and will be completed by the end of 2002.

6 REFERENCES

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