INDIANA UNIVERSITY CYCLOTRON OPERATION FOR PROTON THERAPY FACILITY*

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Abstract

Indiana University has designed and finished construction of the Midwest Proton Radiotherapy Institute (MPRI) [1] consisting of one treatment room with two fixed horizontal beam lines and two treatment rooms with isocentric gantries. The first treatment room has been operating since February 2004, while the first Gantry treatment room has been in use treating patients since April 2007. The proton therapy facility is based on the IUCF K220 separated sector cyclotron, which provides a fixed 208.4 ± 0.1MeV beam to the end user. Each treatment room is designed to set its own energy for treatments and to operate independently from the setup in adjacent rooms. This allows IUCF to deliver beam to Radiation Effect Research Program (RERP) [2] between patient treatments. In this paper we discuss the key design decisions that enabled IUCF to support multi-user operation and our operational experience delivering beam to a medical facility.

IUCF FACILITY DESCRIPTION

IUCF K220 cyclotron delivers constant energy beam to a 57m Trunk beam line, which can feed beam on demand to either one of the three treatment rooms (TS1, TS2 and TS3) or to RERP. When not in use, the proton beam is parked in the beam dump, which contains a Multi-Layer Faraday Cup (MLFC) to monitor and maintain beam energy out of the cyclotron at 208.4MeV. The general layout of the IUCF facility is shown in Fig.1.

The first section of the Trunk Line has achromatic optics to compensate for position and momentum dispersion in the beam extracted from the cyclotron. This improves beam stability and alignment along the Trunk Line. The subsequent telescopic sections of the Trunk line generate the beam double focus condition for each Treatment room. A set of wire scanners monitor beam focusing conditions, while the beam position monitors distributed along the Trunk Line facilitate beam alignment. The beam focusing and alignment conditions are both important for optimal beam transmission into the treatment rooms.

Beam is deflected into the treatment rooms and into the RERP beam lines using fast ferrite magnets with 3ms rise/fall time. Each treatment room has independent energy setup using a beryllium double wedge energy degrader. The double wedge geometry provides continuous energy adjustment that varies residual range in water from 4cm to 27cm with 1mm precision.

Identical doubly achromatic Energy Selection (ES) beam lines transmit the degraded beam into the three treatment rooms. TS1 has two fixed horizontal treatment nozzle systems, while TS2 and TS3 are each equipped with a 360-degree iso-centric gantry manufactured by IBA[3]. The optics of the ES beam line is based on a double bend spectrometer to optimize momentum selection with an adjustable slit installed in the middle, and to minimize neutron background in the treatment rooms from the energy degrading process. The second bending magnet is cast into a concrete wall separating the treatment room from the Trunk Line beam corridor.

The science research area includes the Low Energy Neutron Source (LENS) [4] and Radiation Effect Research beam lines. The LENS facility is based upon high intensity RFQ-DTL system that operates independently from the cyclotron. The Radiation effect program shares the cyclotron beam with MPRI clinic.

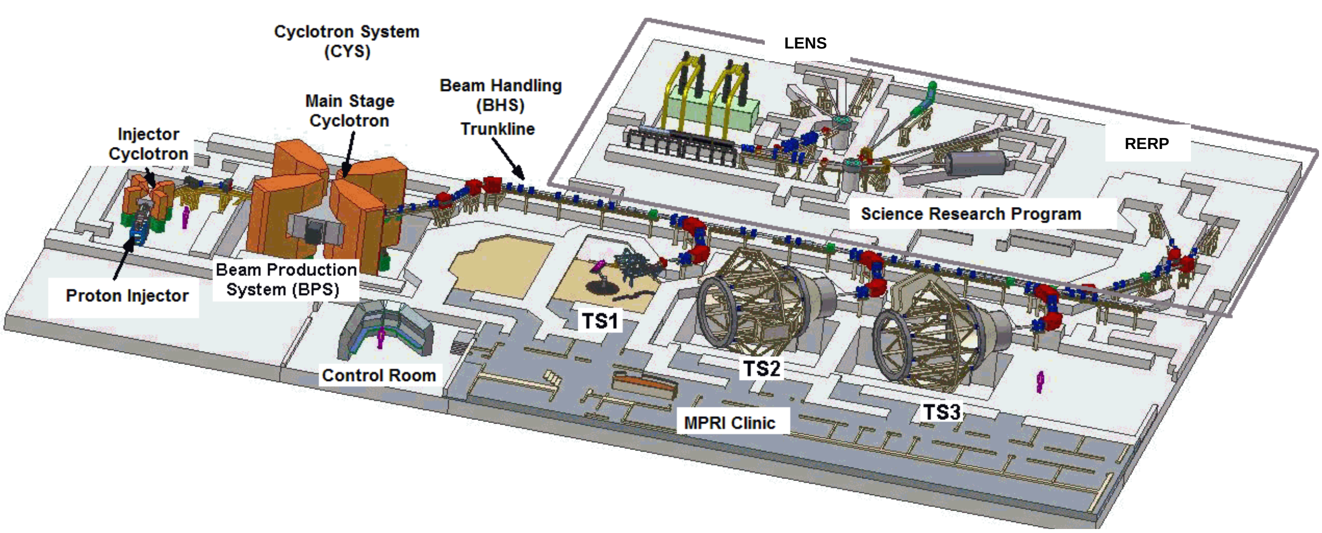

Figure 1: Layout of the IUCF facility including the MPRI clinic and research area.

OPERATIONAL EXPERIENCE

Cyclotron operation for a medical facility imposes several stringent requirements on beam quality delivered to the user. Below we summarize IUCF experience operating and servicing medical facility.

Beam Energy Control

Precision control of the beam energy is important for accurate dose delivery to the prescribed depth as well as for preventing beam misalignments in the transmission lines. The beam energy variation at the beam dump never exceeds 0.1MeV with standard deviation of 0.04MeV around the mean value. This translates to highly reproducible (within ±0.5mm) measurements of the beam penetration range during clinical quality checks. Prior to transmitting the beam into the treatment room, the beam energy, momentum spread and intensity are verified using the movable MLFC in the middle of the ES beam line. Together with energy monitoring in the beam dump MLFC, beam energy verification in each ES beam line leads to a high confidence level in the accuracy of dose delivery to the prescribed depth.

Beam Intensity

A medical proton accelerator must be able to deliver beam intensity sufficient to treat large target volumes to doses of about 2Gy in 1min. The treatment field size at MPRI may reach 30×30cm in size, while the range may be modulated over 19cm to generate a Spread-Out Bragg Peak (SOBP). In practice, between 0.5 and 5nA of beam must be delivered into the gantry nozzle, which uses active beam spreading and energy stacking for delivering dose to the target volume.

A significant fraction of the beam is expected to be lost during the energy degrading process, which would translate into high beam intensity requirements for the cyclotron. Several design decisions alleviated the beam intensity constraints, and routine operation of the IUCF cyclotron does not require more than 50nA of beam delivered to the Trunk beam line. Beryllium was selected for the energy degrader material to minimize beam emittance growth due to multiple scattering. Contrary to popular belief, the neutron production cross-section for 200MeV proton beam is lower for beryllium compared to carbon [5]. Therefore, a beryllium degrader also generates less secondary radiation. The other design features that maximized beam transmission into the treatment rooms include beam double focus condition at the degrader and good momentum acceptance of the ES beam line. The momentum acceptance of the ES line is defined by the 10cm aperture of the quadrupoles and by the maximum value of the dispersion function, which reaches 2.25m.

$$\frac{\Delta p}{p} = \frac{0.5 \cdot Aperture}{D_x} = 2.2 \cdot 10^{-2}$$

The resulting ±3MeV acceptance matches the expected energy spread (FWHM=6.5MeV) of the beam degraded to 70MeV. In contrast, the maximum dispersion in the gantry quadrupoles reaches 3.5m while their aperture is limited to 5cm. This results in a factor of 3 reduction of the gantry momentum acceptance, which also reduces beam transmission into the gantry.

Momentum Spread of the therapeutic Beam

Control over beam momentum spread is often required in the design of a proton radiation facility. Mono-energetic beam would provide the sharpest dose gradient at the distal end, but the width of the resulting Bragg peak would vary significantly for different beam energies. The shape of the Bragg peak is critical in generating uniform dose distribution in depth (SOBP) and the energy dependence of the Bragg peak width would require different libraries of range modulating devices (Propellers or Ridge filters)[6]. Therefore, it is advantageous to maintain the shape of the Bragg peak by controlling the momentum spread of the beam.

The design of the beam delivery system for MPRI includes an adjustable horizontal slit in the middle of the ES beam line where the dispersion is large enough to implement momentum spread control. In reality, the width of the Bragg peak measured in the fixed horizontal beam line varies little over the wide range of treatment energies as shown in Fig.2, which indicates that the energy acceptance of the ES beam line matches the beam energy spread from the degrader. This feature enables MPRI to use a single library of range modulating propellers in the fixed horizontal beam line without relying on momentum spread control. We do observe significant energy dependence of the width of the Bragg peak in the gantries due to their small energy acceptance. However, the momentum spread control is not important since both gantry rooms use an energy stacking method for generating SOBPs which takes into account the shape of the Bragg peak in determining the relative weights of each energy layer.

We conclude that while control over the momentum spread is useful for passive scattering systems, it is not as important for active beam spreading systems.

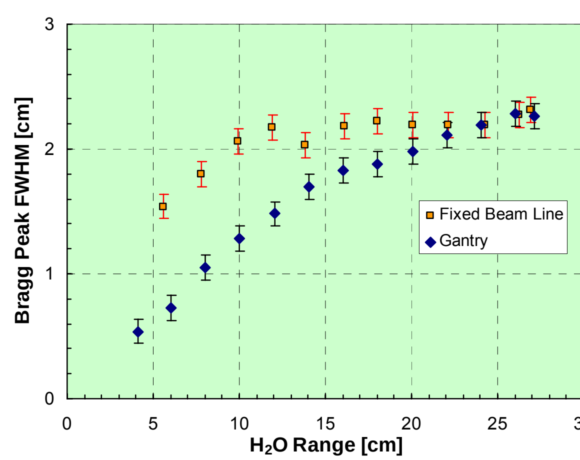

Figure 2: Bragg peak Full Width at Half Maximum as a function of beam penetration range in water.

Multi-User Operation

An important aspect of the IUCF mission is to support biomedical and material science research. Two experimental beam lines were constructed at the end of the Trunk beam line to pursue applied research in radiation effects.

During 25 years of operation for nuclear physics research, IUCF has developed and successfully used beam splitting, which enabled several experiments to take data concurrently. This concept was included in the MPRI facility design, but has not been implemented yet. Each treatment room has an independent control over the treatment setup. The fast ferrite kicker magnets deflect beam from the Trunk beam line to the user either in the clinic or in research beam lines. Each kicker system has a timing signal input to allow operation according to preset beam sharing rules. The typical patient setup time ranges between 15 to 30 min, while the treatment itself only lasts 3 min, including the beam verification procedure. With only one treatment room operating during 2006, there was adequate beam time available to RERP users without any active beam splitting. However, with all three treatment rooms performing treatment at the end of this year, there is a growing need to implement automated beam sharing capability envisioned in the original MPRI design.

Cyclotron Operational Reliability

Successful operation of a medical facility requires operational reliability of the accelerator systems of at least 94%, where any accelerator system failure during scheduled clinic operation is counted as down time for the reliability definition above, whether it affects the treatment schedule or not. Since 1974, the reliability of the IUCF separated sector cyclotron, operated for a nuclear physics program, fluctuated between 80% and 94%.

To reach the required reliability for medical operation, cyclotron performance was reviewed and a major refurbishment and upgrade program [7] commenced prior to construction of the MPRI facility. In addition, IUCF established a 4-year program to replace aging major equipment that has been identified as high risk components that are difficult to service and often no longer supported by the manufacturer.

Unfortunately over the past 4 years of delivering beam to the medical facility, the cyclotron operational reliability has been about 91% and met the 94% required goal only in 2005. One recurrent source of down time is the new 750keV CW RFQ pre-injector. The innovative RFQ structure, designed and manufactured by AccSys Technology Inc. [8], replaced the old 600kV Cockroft-Walton pre-accelerator system. The RFQ system was delivered to IUCF only 6 month prior to the start of the treatment room commissioning owing to fabrication delays. RFQ operation in CW mode imposes very stringent constraints on the design of its individual components. Because of the short development time, we have experienced several major breakdowns that identified components that had to be redesigned for CW operation, including the RFQ power amplifier, the contact-less tuning slug, and the drive-loop. After several external design reviews, we anticipate that upon completing the recommended upgrade program, the RFQ will be made as reliable as the rest of the IUCF cyclotron system.

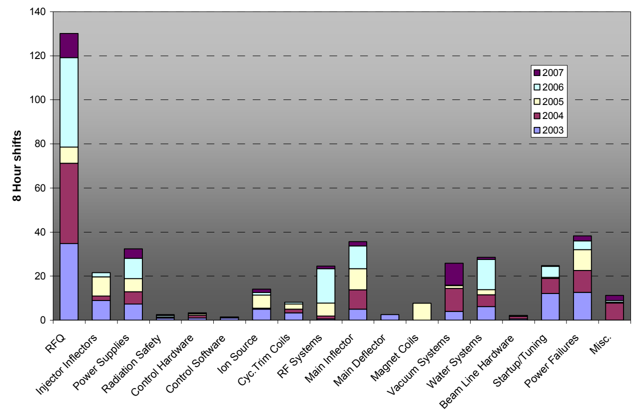

Figure 3: Cyclotron cumulative breakdown summary.

Excluding the RFQ failures, the IUCF cyclotron system reliability was at the 95% level during the last four years. The reliability of the first treatment room that has been in operation for almost 4 years is well over 97%.

CONCLUSIONS

IUCF completed construction of the MPRI facility and has obtained 510(k) approval for the active beam scanning systems in the Gantry treatment rooms. Upon completing the clinical acceptance testing and performing extensive commissioning studies, MPRI started patient treatments using the Gantry treatment system in April 2007.

We hope to further improve service to the MPRI clinic and to the radiation effect users by implementing automated beam sharing, which would include beam gating on organ motion for advanced patent treatments.

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