OPERATION OF A CYCLOTRON BASED PROTON THERAPY FACILITY*

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Abstract

The Northeast Proton Therapy Center has been treating patients with protons for over three years. More that 1000 patients have been treated. Some of the lessons learned, in order to develop a system that is reliable and capable of delivering the desired beam parameters will be summarized. Operational challenges and developments will be discussed.

PROTON THERAPY

The use of protons for the treatment of radiation susceptible disease has been documented previously [1]. The advantages offered by the proton dose distribution are apparent in a number of cases. An example of one case is the treatment plan shown in figure 1 for a pediatric meduloblastoma. In this case, it is seen that the dose is deposited in the spinal area, but the rest of the organs such as the lungs and heart are spared.

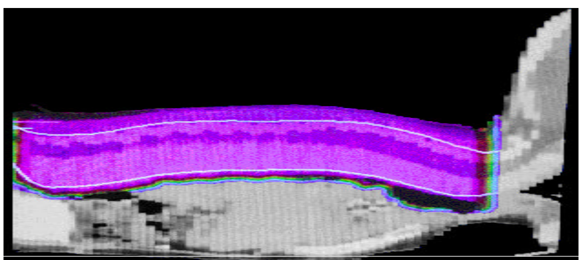

Figure 1. Color wash representation of the dose distribution for a spinal irradiation with protons.

CYCLOTRONS FOR PROTON THERAPY

Cyclotrons have been used as the accelerators to produce the protons for proton therapy for decades. The 88" cyclotron at Berkeley and the Harvard Cyclotron (pictured in figure 2) are among the earliest examples.

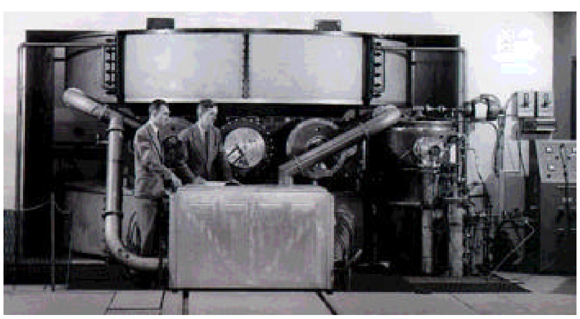

Figure 2. The 160 MeV Harvard Cyclotron.

The Harvard Cyclotron was dedicated in 1949 and had a long career in Nuclear Physics, the Manhattan Project, and finally decades in Proton Therapy. It was decommissioned in 2002. For some time Proton Therapy was carried out in the environment of an accelerator laboratory such as TRIUMF and PSI. Of course the cyclotrons in these laboratories were too massive and operationally complex for use in a hospital environment. More recently the IBA Compact C230 Cyclotron weighing 200 tons [2] and the ACCEL superconducting cyclotron weighing only 90 tons [3] have been designed and built specifically for the purpose of proton therapy. Hospital based used is now possible.

Figure 3. The IBA C230 Cyclotron (above) and the ACCEL Superconducting Cyclotron (below).

Northeast Proton Therapy Center

The Northeast Proton Therapy Center [4] is on the main campus of the Massachusetts General Hospital in Boston and has been treating patients since November 2001.

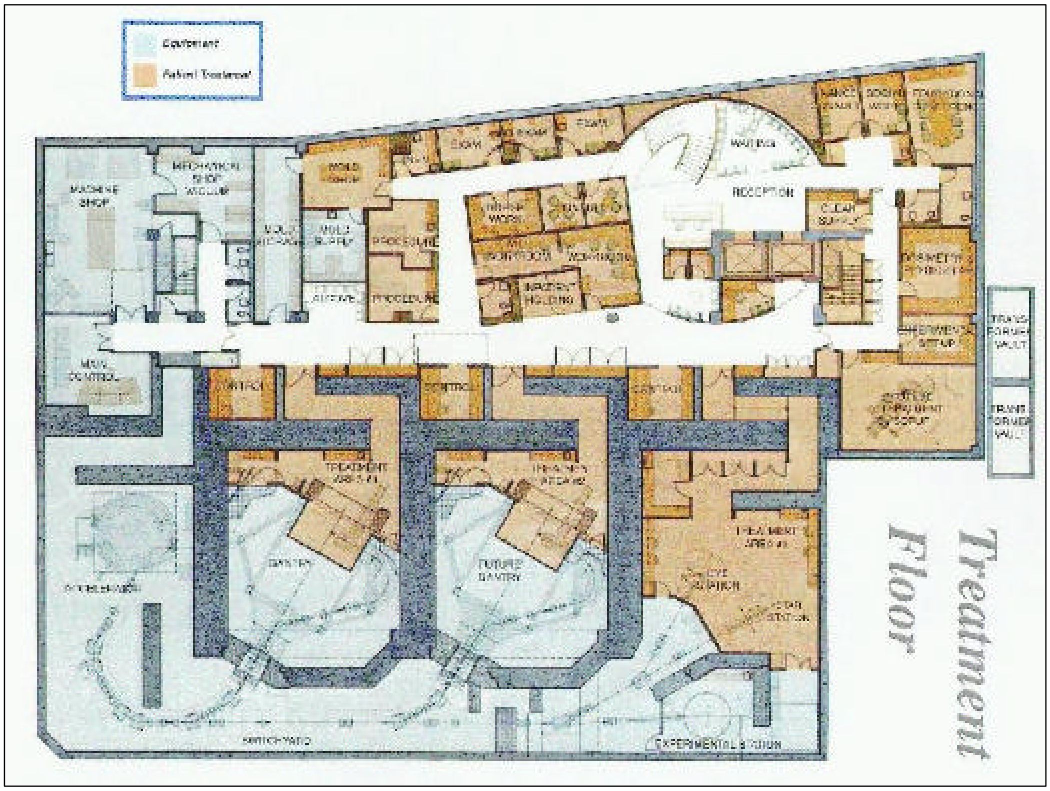

Figure 4. Physical Layout of theNortheast Proton Therapy Center. This facility includes the IBA C230 Cyclotron and Energy Selection System, Beamline, Two Gantry Treatment Rooms and a Fixed Beam Room with 3 Beamlines.

The facilities include:

- Two Treatment Rooms with Isocentric Rotating Gantries.
- One Fixed Beam Room with two beam treatment stations, including an eye treatment facility and a Stereotactic treatment facility.
- An experimental beamline.

OPERATIONAL PARAMETERS

In order to operate the accelerator facility in a manner suited to patient treatment it is necessary to understand the parameters that are relevant to these treatments and the tolerances necessary. Essentially the Range in the Patient and the Dose Rate are related to the following Cyclotron Parameters:

- Rf System
  - Dee Voltage
  - Overall Stability
- Extraction Efficiency
  - Tolerances on Extraction Devices
  - Component Alignment
- Energy Selection System Efficiency
- Ion Source
  - Lifetime
  - Physical Source Characteristics

Energy Selection System

Figure 5 shows the efficiency of the Energy Selection System. Since the Cyclotron is a fixed energy accelerator, a graphite degrader is used to modify the beam energy. The energy selection system constrains the beam phase space to match the acceptance of the beamline, with a resultant loss in beam.

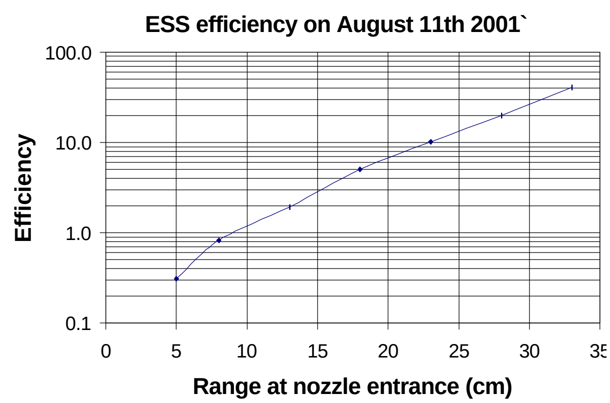

Figure 5: ESS Efficiency

Extraction Efficiency

In order to produce the desired dose rate, it is necessary to extract at least 300 nA with efficiency that is consistent with an operational Dee Voltage, a reasonable source lifetime and good stability. Initially the extraction efficiency was very low owing to the presence of several resonances in the cyclotron. In order to get beam to the extraction point several magnetic field modifications were necessary and an asymmetric powering of the Cyclotron coils is necessary. Finally the positioning of the pole end caps and the of the Gradient Corrector proved to be very sensitive. Fractions of a mm accuracy were necessary to achieve a workable extraction efficiency. Figure 6 shows the results of radial probe scans taken during the process to improve the extraction efficiency.

After careful adjustment, it was possible to achieve an extraction efficiency of about 25%. On average it is between 20% and 25%. The newer IBA C230 Cyclotrons considered the resonance issues in the design and achieve a higher extraction efficiency.

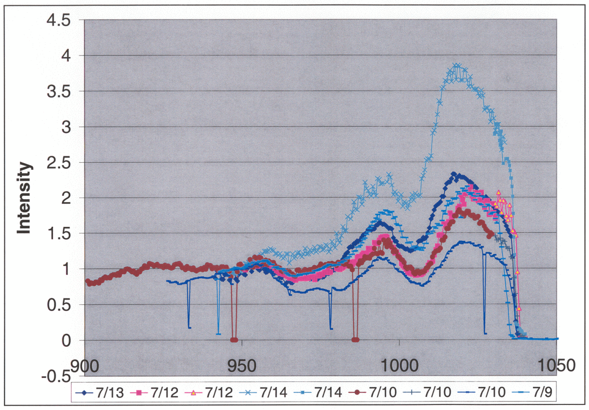

Figure 6. Several radial probe scans for different Gradient Corrector geometries in the last 10 cm of the Cyclotron radius. The vertical axis is relative intensity.

Extracted Beam Properties

With the gradient corrector adjusted for extraction efficiency, the extracted beam properties are determined. A large sextupole component arising from the cyclotron pole edges and the gradient corrector results as shown in figure 7. Luckily, in the case of the operation for proton therapy this situation is not detrimental. The beam is focussed down near the energy degrader, and for most of the Energy range used, the degraded beam scattering dominates the beam phase space.

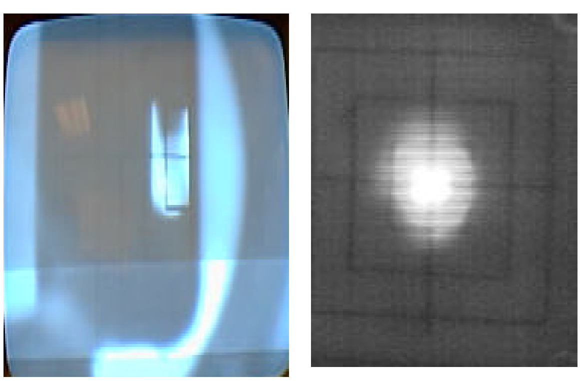

Figure 7. Extracted beam spot showing sextupole component (on left) and after focussing (on right).

AUTOMATED OPERATION

A medical facility requires a smooth operation with availability greater than 95%. It normally cannot support a large expert staff of accelerator personnel. Therefore a high premium is placed on automation and ease of operation.

Some of the issues for automated operation include:

- Day-to-day reproducibility
- Intra-day stability

In practice this means a significant amount of feedback capability, if the system is not perfectly stable by design. Some examples of feedback system include:

- Extracted Current
- Yoke Temperature correlation to Main Coil Power
- Ion Source Operating Point
- Rf Frequency Optimization

At present at NPTC, the first two are operational and implementation of the second two are underway.

There is a clear need for these loops owing to the sensitivity of the cyclotron parameters. Figure 8 below shows the extracted current as a function of a frequency scan. Note the sharp variations in operating parameters. These variations change as the temperature and/or other parameters yet to be determined, of the system changes.

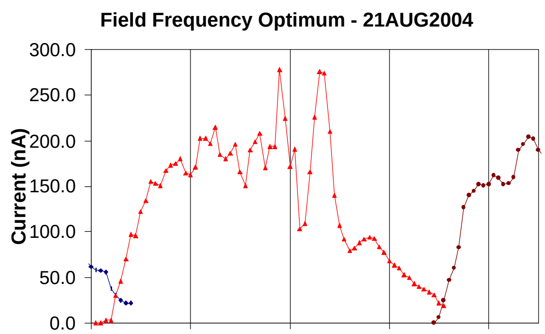

Figure 8. Frequency Scan with measure output current

Of particular complexity is developing an algorithm for the appropriate Ion Source settings to produce the correct current for the desired patient dose rate. The parameters that affect these settings include:

- Source Lifetime
- Rf Frequency
- Rf power
- Other unknowns

Therefore, it is necessary to create a calibration sequence when the cyclotron is not in use for treatment in order to develop a lookup table. This must be done every few minutes to a half hour in order to keep ahead of parameter fluctuations.

Reliability

The most important parameter for automation and availability is the reliability and maintainability of the hardware. The system now performs at close to a 95% availability. The cyclotron has a higher availability figure. This was achieved after replacing many of the internal cyclotron components. After some years of experience it would become clear that one system or another needed improvement. For example we currently use the third version of the electrostatic deflector which is machined from a solid block of copper. This together with an appropriate resistor chain has proven to give a high level of reliability. Figure 9 shows a view of the current version of the deflector.

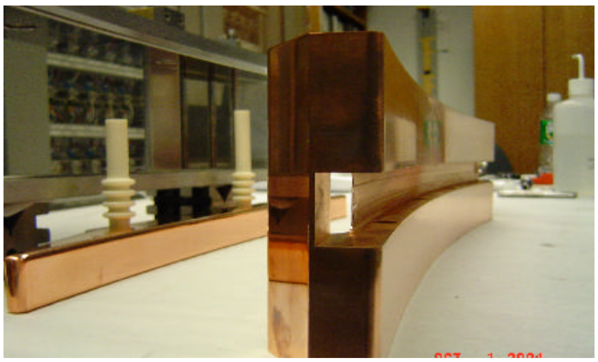

Figure 9. Current version of electrostatic deflector

One modification that gave significant improvement in Rf reliability is the replacement of the Oil Diffusion Pump system with a Cryopump system. While not all the authors on this paper agree with this conclusion, the last year of operation at NPTC has proven to be very stable with respect to the Rf power levels. There was one incident which resulted in an episode of higher rf power, but this was traced to vacuum grease deposited on the rf cavities.

SYSTEM CAPABILITIES

The Proton Therapy System fed by the C230 accelerator has proven to be a very capable and powerful system. The CW output together with a fast and flexible Ion Source control makes a system that can produce a very flexible current output. This can be used both for the passive scattering system [5] and for the future scanning system that requires intensity modulation. Figure 10 shows some examples of beam current modulation. This is synchronized with the rotating range modulation system so that the appropriate dose is deposited as a function of range thus creating a “Spread Out Bragg Peak” with the appropriate uniformity and width.

The Ion Source can be modulated together with a scanned beam to produce an arbitrary dose pattern. Two such patterns is shown in Figure 11.

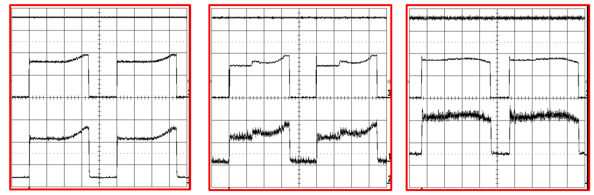

Figure 10. Beam Current Modulation Examples. The upper trace is the desired function and the lower trace is the actual cyclotron output.

Figure 11. “Arbitrary” raster scan patterns using Intensity modulation of the Ion Source.

CONCLUSIONS

The Northeast Proton Therapy Center is on the way to achieving the desired Cyclotron operation. In just over 3 years of patient treatment operation nearly 1000 patients have been treated. Beam current modulation for passive scattering and raster scanning beam delivery systems have been demonstrated.

Operational reliability is steadily improving with increased experience and component redesign. Much has been learned about the design of reliable systems from the point of view of availability, maintainability and reliability. There has been a clear lesson that the cost of designing reliability up front is much less than the cost of having to develop it during an on-going program.

Above all, there needs to be a good team relationship between the machine builders and the user community, in this case the medical community so as to clearly share the requirements and the limitation of the facility. There is nothing so bad as the reaction of a patient who cannot be treated on a given day, and nothing so rewarding as a patient who has completed a treatment regime that can only be offered by the technology realized using a proton accelerator, in this case a cyclotron.

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