THE RAPID CYCLING MEDICAL SYNCHROTRON, RCMS

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1 INTRODUCTION

Thirteen hadron beam therapy facilities began operation between 1990 and 2001 – 5 in Europe, 4 in North America, 3 in Japan, and 1 in South Africa [1]. Ten of them irradiate tumors with protons, 2 with Carbon-12 ions, and 1 with both protons and Carbon-12. The facility with the highest patient throughput – a total of 6174 patients in 11 years and as many as 150 patient treatments per day – is the Loma Linda University Medical Center, which uses a weak focusing slow cycling synchrotron to accelerate beam for delivery to passive scattering nozzles at the end of rotatable gantries [2, 3, 4]. The Rapid Cycling Medical Synchrotron (RCMS) is a second generation synchrotron that, by contrast with the Loma Linda synchrotron, is strong focusing and rapid cycling, with a repetition rate of 30 Hz [5, 6, 7]. Primary parameters for the RCMS are listed in Table 1.

Table 1: Primary parameters of the RCMS facility.

Min/max extraction energy [MeV]	70/250
Repetition rate [Hz]	30
Maximum protons per bunch	1.7×10^9
Average protons per bunch	0.3×10^9
Maximum flux, [protons/min]	3.0×10^{12}
Average scanning flux, [protons/min]	0.5×10^{12}
Ave. dose rate (250 MeV) [Gy-liter/min]	20
Vert. beam size (250 MeV) [mm]	0.9
Total horz. size (250 MeV) [mm]	2.5

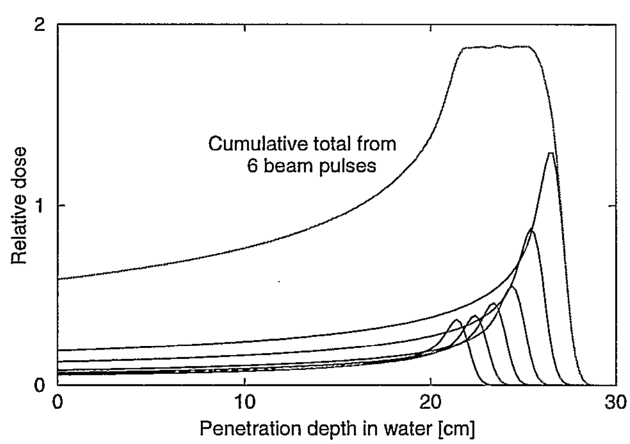

Figure 1: Spread out Bragg peak from 6 beam pulses.

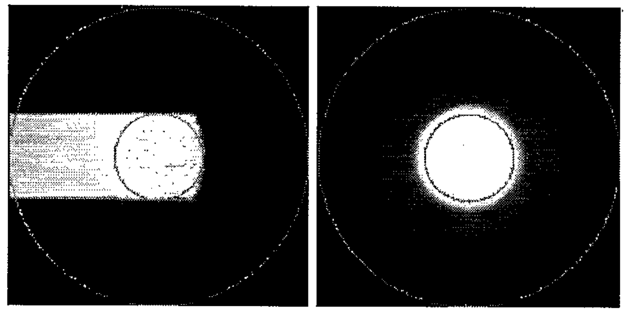

Figure 2: Simulated dose to a 6 cm tumor in a 20 cm phantom. The collateral dose is much more with beam delivery from one angle (LEFT) than from many angles (RIGHT).

2 PATIENT TREATMENT PHYSICS

Proton therapy is an effective and non-invasive way to treat tumors deep within the body because the protons deliver most of their dose just before stopping, in the Bragg peak. Figure 1 shows how the longitudinal dose from multiple beam pulses can be added up to deliver a total dose that is flat over the depth of the tumor. In this case 6 pulses with different energies and an RMS energy spread of 2 MeV deliver a dose that is flat to 1% over a plateau about 5 cm long. However, Figure 1 also shows that if all the beam comes from the same direction – in a "single field" treatment – then the collateral dose at the surface of the patient is still approximately 30% of the dose at the tumor.

This is illustrated on the left of Figure 2, which shows the integrated dose delivered to a hypothetical tumor in a cylindrical phantom. The collateral dose is enormously reduced with tomotherapy, when the therapeutic dose is delivered from many different angles – the collateral dose on the right of Figure 2 is barely visible. Figure 3 shows that the dose at the surface of the patient is reduced to about 5% with tomotherapy. This is much less than the 30% value for single field irradiation with protons, and about a factor of 10 less than the collateral dose from X-rays delivered with Intensity Modulated Radiation Therapy (IMRT) from many angles, as also shown in Figure 3.

The effects of multiple scattering and energy straggling are important. Figure 4 shows that the transverse beam size is dominated by multiple scattering, if the incoming parallel beam size is at the 1 mm level or less [8]. Similarly, the RMS energy spread of 2 MeV that was used in Figure 1 is typical, even for a mono-energetic incoming beam.

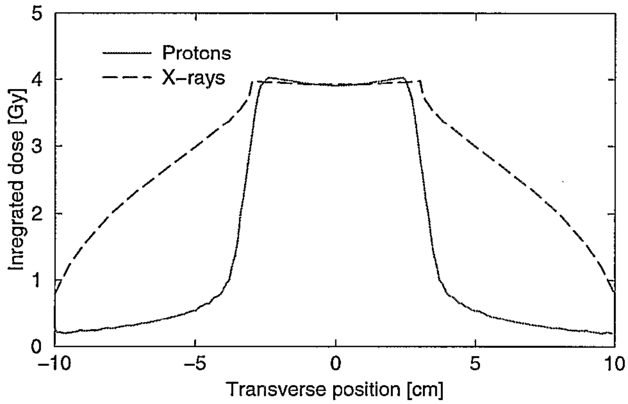

Figure 3: Integrated dose from tomotherapy of a 6 cm tumor using protons and X-rays. The collateral dose with protons is an order magnitude less than with X-rays.

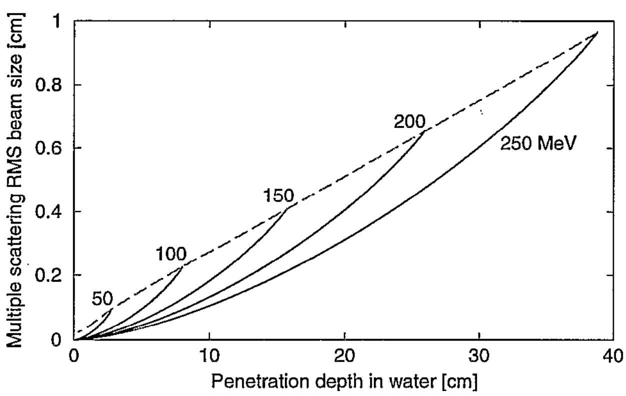

Figure 4: Transverse beam size due to multiple scattering.

3 CLINICAL REQUIREMENTS ON THE ACCELERATOR

The most challenging top level requirements for accelerator performance in a proton therapy facility follow from the clinical goal of very low collateral dose during 3-D stereo-tactic therapy, as described above.

Raster scanning sharp beams. The sharpest possible pencil beam must be painted in 3-D onto an irregularly shaped tumor from each of many treatment angles. A raster scanning system uses horizontal and vertical steering magnets just before the nozzle at the end of a gantry to move the narrow beam transversely, while the energy is varied for depth control. This is demonstrated in Figures 2 and 1, respectively. In contrast, passive scattering nozzles severely inhibit multiple field treatment, since a beam spreader is used to make a broad uniform transverse beam that inevitably also has an artificially large energy spread. The beam from a passive scattering nozzle is unwieldy, has high losses, generates many neutrons, and requires a different collimator profile for each treatment angle.

Energy flexibility. It is necessary to be able to change the energy of the extracted beam rapidly, over a large range of closely spaced values, in order to rapidly paint the tumor from many angles. This requires robust and repeatable "fast extraction" of all the beam on a single turn of the accelerator. The extraction energy of the RCMS can be changed at a 30 Hz rate (on each cycle) over the entire range from 70 MeV to 250 MeV. In practice the maximum rate of change of delivered beam energy (at least 5 MeV/s) is set by how quickly the beam delivery magnets can change current. In contrast, slow extracted beam requires careful tuning, and expert feedback systems, at each of a small number of established extraction energies.

High beam flux. The largest number of protons need to delivered per minute, in order to treat the largest tumors in the shortest times. This is closely related to the need for rapid acceleration, since the number of protons that a synchrotron can accelerate in each cycle is limited by the space charge effect [3, 4]. Thus, the RCMS with a repetition rate of 30 Hz delivers a average flux much higher than synchrotrons with an acceleration period of a few seconds [9]. In 250 MeV operation the RCMS delivers as much as 20 Gy per minute to a 1 liter tumor. The usual dose per daily treatment is a few Gy.

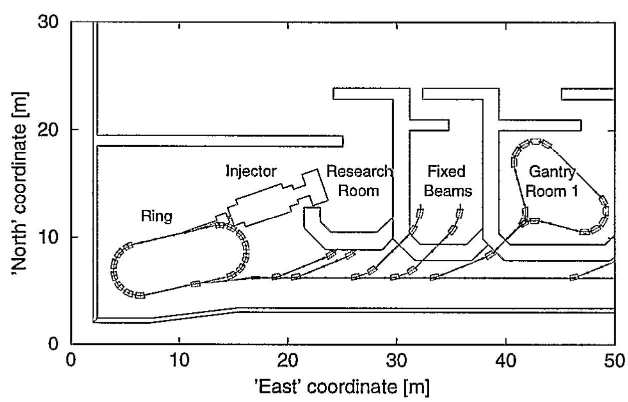

Figure 5: Sample layout of the RCMS facility.

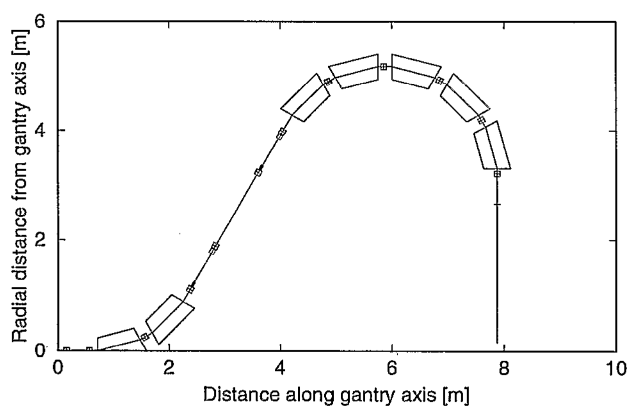

Figure 6: A light weight separated function gantry.

4 RCMS ADVANTAGES

Figure 5 shows a sample RCMS layout, including only the first gantry room. Figure 6 shows the geometry of a gantry with separated function magnets. Note that if there are 4 gantries, then there are about twice as many gantry bending magnets – 720 degrees worth – as there are in the synchrotron itself. Both the synchrotron and the gantry optics use strong focusing to make sharply focused beams [10]. Small beam sizes are not only a clinical necessity, but also enable inexpensive gantries, since small beams permit the use of small, lightweight, magnets which are economical to operate.

Strong focusing optics and small beams are options only available to synchrotron based facilities, and not to cyclotrons [4]). Synchrotrons have further advantages. They consume less than half the power of equivalent cyclotrons, reducing both operating and capital infrastructure costs. Synchrotrons are much more efficient in delivering beam – a much higher percentage of beam gets from the source to the patient. This is especially true of a fast extraction synchrotron like the RCMS. High efficiency means that much less residual radio-activity and far fewer neutrons are generated, so that less shielding is required and building costs are reduced. It also means that a synchrotron facility is easier to handle, since there is instant access for maintenance, and less need to monitor operator and technician dosimetry. Finally, even a weak focusing synchrotron is much lighter than the single massive magnet in an equivalent cyclotron. This also greatly reduces the cost of the building foundations.

The RCMS design chooses simple proven technologies to ensure that the proton therapy facility will have high reliability and availability. For example, rapid cycling synchrotrons with resonant main magnet power supplies have been in operation at many locations, worldwide, for 40 years. Secondly, fast extraction on a single turn is robust and reliable, and avoids the possibility of dumping large amounts of stored beam into a patient. Third, the injection energy is relatively high, at 7 MeV. Finally, and most all of all, strong focusing is used throughout, to keep the beam sharply focused and well under control.

5 SUMMARY

Proton tomotherapy – beam delivery from many angles – enables ultra-low collateral doses in precision 3-D stereotactic tumor therapy. The simplicity, reliability, and flexibility of the RCMS design all contribute directly to superior clinical performance in tomotherapy, and in the treatment of the largest tumors in the shortest times. Building, gantry, infrastructure, and operating costs should all be included when comparing medical synchrotron and cyclotron designs.

Acknowledgements

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