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RCMS – A SECOND GENERATION MEDICAL SYNCHROTRON

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1 PULSED BEAM SCANNING

The Loma Linda University Medical Center treats more than 100 patients per day using a weak focusing slow cycling synchrotron with passive scattering nozzles at the end of rotatable gantries [1, 2, 3]. The Rapid Cycling Medical Synchrotron (RCMS) is a second generation synchrotron which will achieve the performance listed in Table 1, including rapid 3-D Pulsed Beam Scanning [4, 5].

Figure 1 shows the cumulative longitudinal dose from 6 beam pulses with different energies and an RMS energy spread of 2 MeV, flat to 1% over a plateau about 5 cm long. Figure 2 shows that the transverse beam size is dominated by multiple scattering, if the incoming size is at the 1 mm level [6]. It takes 10 overlapping beam pulses 0.5 cm wide to scan a tumor 5 cm wide with 1% flatness. Thus it takes

$$T_{pass} \approx (10 \times 10 \times 6)/f_{rep} \approx 10 \ \text{seconds} \qquad (1)$$

for a single pass over a tumor $5\times5\times5$ cm, where $f_{rep} = 60$ Hz is the beam pulse repetition rate. Two or 3 passes are required, for a typical scanning time of 30 seconds. Small beam sizes are critical for inexpensive gantries, since small beams permit the use of small, lightweight, magnets which are economical to operate. The RCMS achieves small beam sizes by applying “strong focusing” optics to a small emittance beam (natural to synchrotrons, but not to cyclotrons [3]). Figure 3 shows a sample RCMS layout.

Table 1: Primary performance parameters.

Patient treatments per day	300
Scanning treatment time (typical) [s]	30
Maximum dose rate [Gy-liter/min]	$\sim$ 300
Min/max proton energy [MeV]	70/250
Repetition rate, f_{rep} [Hz]	60
Protons per bunch, N	3×10^9
Accelerated flux, [protons/min]	1×10^{13}
Vert. beam size (250 MeV), σ_y [mm]	0.9
Total horz. size(250 MeV), σ_x [mm]	2.5

2 GANTRIES AND NOZZLES

A conservative gantry with separated function magnets is shown in Figure 4. The spaces between dipoles (for flanges and quadrupoles) are eliminated all together in an alternative design using combined function magnets. Both designs use only two main magnet power supplies, minimizing the number of parts that might fail. Small magnets with narrow apertures are possible because the beam is small, and because any scanning dipoles are located downstream of the gantry arc. The mechanical support structure has to keep the gantry isocentric within a 1 mm diameter sphere under all rotation angles. This requires careful optimization of the mechanical structure for weight and stability. First conceptual design considerations indicate a weight of roughly 50 tons for an optimized support structure. Conversion between scanning and passive scattering nozzles is possible – the space of 3.2 m from the last dipole to the patient is available either for the longer passive scattering nozzle, or for leverage to scan the beam over an area of ±10 cm.

3 CONTROLS SYSTEMS

There are three RCMS control systems: the accelerator control system, the treatment control system and the patient planning software system. The design philosophy is to keep these three as independent and compartmentalized as possible. We prefer to commission the subsystems independent of one another, minimize software, be able to understand the state of the system at any given point in time, apply redundant measurements and checks, and use proven industrial solutions for databases and slow control process systems.

Accelerator Control System The accelerator control system design will be patterned after the National Synchrotron Light Source system presently in use at BNL. The accelerator has its own beam monitoring system, independent of the treatment control system. Communication between the accelerator and treatment control systems is kept to a minimum. A single table of information, representing the dose delivery profile, is downloaded to the accelerator system for each patient. Once treatment has begun accelerator control is only through hardware interlocks.

Treatment Control System The treatment control system (TCS) measures several beam related quantities: positions, sizes, intensity, integrated dose, energy, and the necessary scanning parameters. The TCS compares the measured quantities with those sent to the accelerator control system and decides whether the treatment is proceeding properly. If any deviation is found, a beam interlock mechanism is activated. These systems are designed at minimum to approved industry approved standards, ANSI/ISA-S84.01-1996, “Application of Safety Instrumented Systems for the Process Industries”. Additional FDA standards will also apply. The basic premises defining the TCS design philosophy follow and build upon the system implemented at GSI [7]. The GSI system has operated and treated patients successfully in a raster scan mode. We intend to pursue a fully redundant system of measurements, calculations, and comparisons, employing a real-time operating system, hardware and firmware based, housed in a VME

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

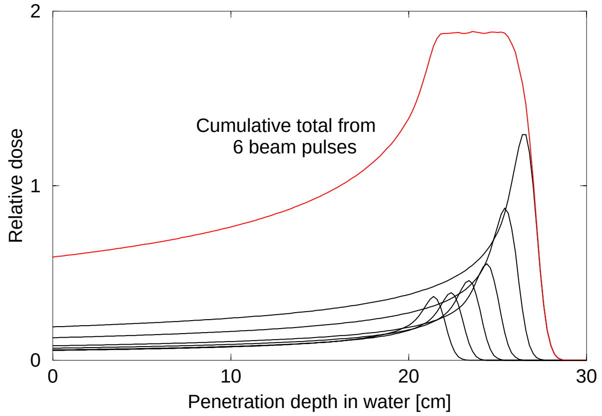


Figure 2: Transverse beam size due to multiple scattering.

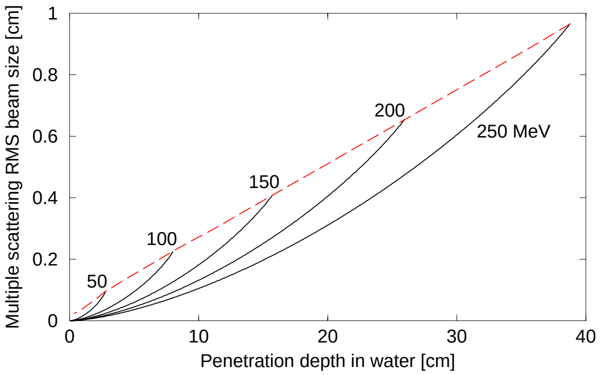


Figure 3: Sample layout of the RCMS facility.

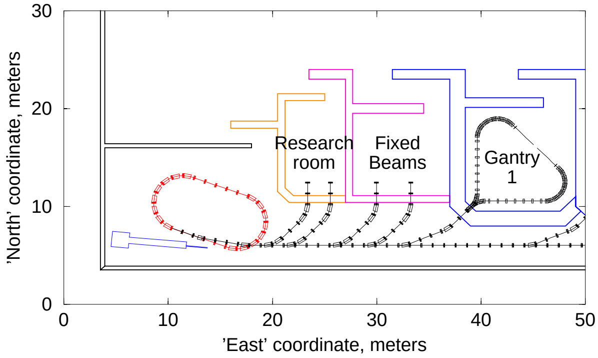


Figure 4: A light weight separated function gantry.

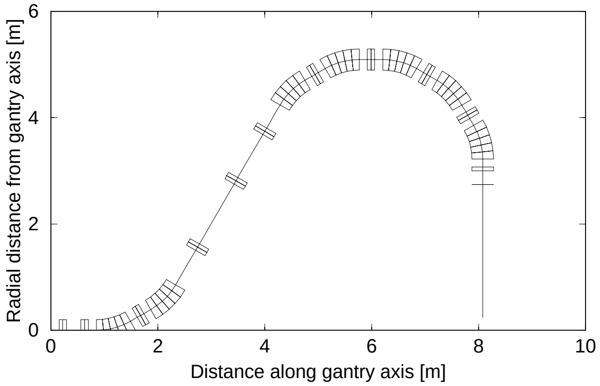


Figure 5: Layout and optical functions for the synchrotron.

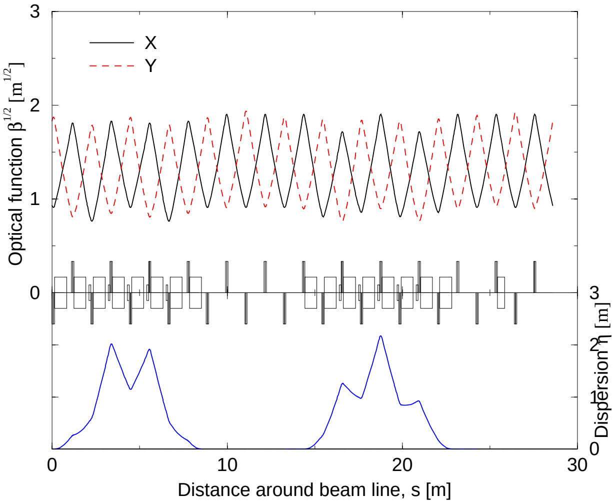
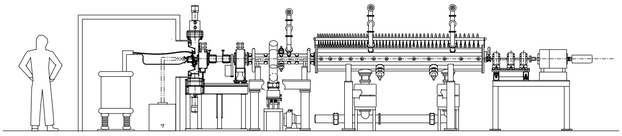


Figure 6: Injector side elevation sketch.



architecture. Traditional PC software is used only as the interface to view the state of the system, and plays no role in the dose application or safety systems. Industrial systems will be used for the control and monitoring of chamber high voltages, gas systems, low voltage and magnet power supplies, as well as recording histories of system variables.

Patient Planning Software The patient planning software (PPS) interfaces with the treatment control and the accelerator. The PPS task is to deliver the table containing information about the specifics of the patients dose.

4 SYNCHROTRON AND LINAC

The racetrack synchrotron shown in Figs. 3 and 5 uses identical FODO half-cells in a *strong focusing* scheme to simplify the design, and to reduce the vertical and horizontal beam sizes to the small values shown in Table 1. The *rapid cycling* rate of 60 Hz allows small acceleration currents to achieve high treatment dose rates – each cycle can carry about the same number of protons as a slow cycling synchrotron with a repetition rate of less than 1 Hz. Low currents simplify the design and reduce the risk of large accidental doses to the patient. *Fast extraction* takes the beam out in a single turn, avoiding the complex feed back systems which are necessary to reduce spill fluctuations with slow extraction. The robust, highly repetitive nature of the RCMS makes it easy to accurately control the intensity and energy of each pulse, by adjusting a timing gate in the linac, and the timing of the extraction kick. Strong focus-

Table 2: Accelerator technology comparisons (adapted from [3]). AHAN*: As High As Necessary. These intensities can exceed 100 μA but they can be hardware limited at the ion source to the 30 to 300 nA range. N/A: data not (yet) available.

Type	Synchrotron (rapid cycle)	Synchrotron (slow cycle)	Cyclotron	LINAC
Energy level selection	continuous	continuous	fixed	continuous
Intensity limit [10^{12}/mn]	$\gg$10	5	AHAN*	AHAN*
Size (diam. or length) [m]	10	6	4	37
Average power (beam on) [kW]	$\sim$ 200	370	300	320
Emittance (RMS unnorm.) [μm]	0.2	1–3	10	0.1
Repetition rate [Hz]	60	0.5	continuous	300
Duty factor (beam-on time)	pulses	20%	continuous	0.1%
Intensity uniformity (scanning)	excellent	adequate	good	good
Beam extraction efficiency	$\sim$ 99%	90%	N/A	N/A
Energy spread (typical) [10^{-3}]	$\pm$1	$\pm$1	$\pm$5	$\pm$1
Energy stability [10^{-3}]	$\pm$0.3	$\pm$1	N/A	$\pm$1

ing makes the magnets inexpensive, while fast extraction and rapid cycling enable robust and rapid 3-D scanning.

Rapid cycling leads to particular (although not unprecedented) challenges in three areas. A resonant arc dipole power supply avoids large reactive power loads on the grid by compensating the reactive effects of the dipoles with energy storage capacitors [5]. This is energy (and cost) efficient. The Radio Frequency (RF) system challenge lies in the rapid change of the revolution frequency as the protons accelerate. The accelerating voltage and the beam loading are modest, so a non-resonant RF system can be used, including an off the shelf solid-state amplifier of less than 5 kW [5]. This is a great advantage over using the more common vacuum tube amplifiers. The beam pipe challenge comes from the strong eddy currents that would be induced in a conventional “thick” metallic beam pipe [8]. The RCMS will use either a ceramic beam pipe with a conducting surface layer, a ribbed thin metal pipe, or a composite beam pipe with an internal metal foil.

The linac injector shown in Figure 6 comprises a multi-cusp plasma type proton source, a Radio Frequency Quadrupole (RFQ), and a single tank Alvarez type Drift Tube Linac (DTL). The front section of the RFQ bunches the 30 keV beam from the ion source, before accelerating it to 3.0 MeV. The DTL then accelerates the beam to the final injection energy of 7.0 MeV, using a ramped gradient tank design (from 1.0 to 2.0 MV/m) with a total length of 2.9 meters. Injection into the ring is accomplished by a synchrotron kicker with a 250 ns flat top. The relatively high synchrotron injection energy makes the protons more dynamically rigid, ameliorating space charge effects and reducing the RF frequency swing.

DTLs routinely provide rms normalized emittances far lower than the RCMS requirement – an output transverse rms emittance of 0.1 μm for a 20 mA beam (at 1.76 MeV) is typical. At the low RCMS current of about 2.1 mA the emittance can be even smaller, much less than the detuned value of 0.15 μm that is specified. A chopper trims the linac bunch to a length in the range from about 25 ns to 250 ns, and absorbs the unused portion of the beam that is not injected into the synchrotron. The chopped bunch length is continuously variable throughout this range, pulse-by-pulse. In addition, the ion source control system permits the continuous selection of output current from 0.2 to 2.1 mA. Thus, the bunch intensity has a dynamic range of more than two orders of magnitude. It is expected that a pulse-to-pulse jitter tolerance of 1% can be met over the entire intensity range.

5 TECHNOLOGY COMPARISON

Following Coutrakon [3], Table 2 compares four different proton therapy accelerator technologies. The RCMS can achieve faster changes in the beam energy than the other circular accelerators with a much smaller emittance, a moderate size and the adequate intensity for proton therapy. The fixed energy of the beam extracted from a cyclotron is reduced to the desired energy by a variable thickness energy degrader. In this sense the delivered energy selection is variable, at the expense of a higher emittance from multiple scattering, larger gantries, and higher radio activation – leading to higher shielding requirements.

6 REFERENCES

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