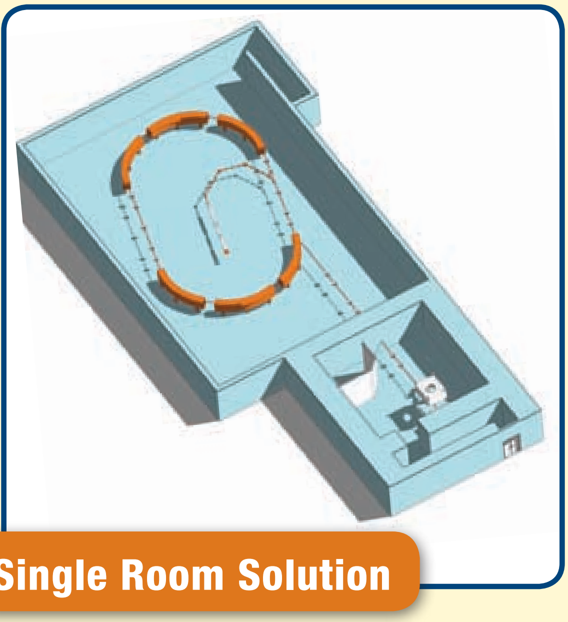
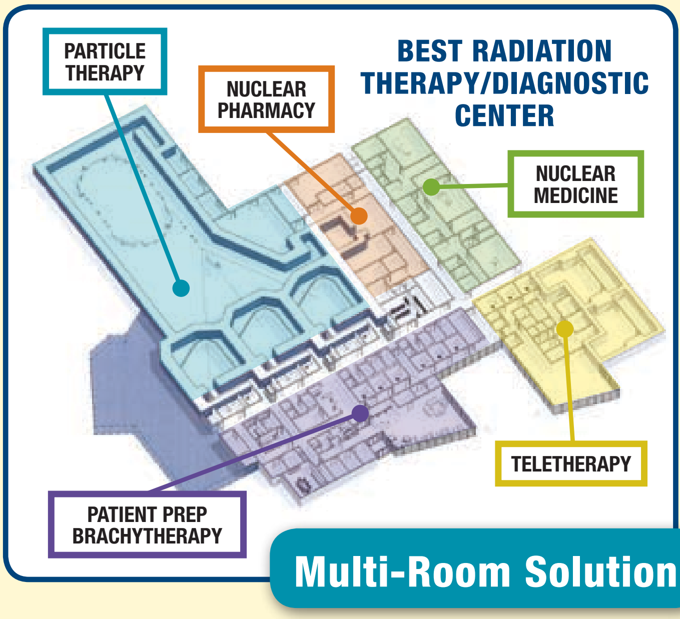
Best® Particle Therapy

Introducing ... Best Medical Synchrotrons with variable energy from proton to carbon, in Single or Multi-Room Solutions, with or without Gantry!



Single Room Solution



Multi-Room Solution

Best Particle Therapy, Inc. is a new member of the TeamBest® family of companies, founded by Krishnan Suthanthiran in 1977. TeamBest® currently offers products for brachytherapy and teletherapy. Best NOMOS, a TeamBest® company, invented IMRT (intensity-modulated radiation therapy) in the early 1990s. TeamBest® continues to expand its product offerings to cover low tech to high tech with the primary goal of making these technologies affordable and accessible globally. Best Particle Therapy will utilize advanced state-of-the-art accelerator technologies and provide cost-effective solutions for particle therapy treatment and research.

"Particle Therapy" (PT) is a radiotherapy technique that utilizes hadrons and was first proposed by R.R. Wilson in 1946 after analysis of inverted depth-dose distribution measured at the Berkeley Cyclotron. This analysis resulted in the first radiological use of hadrons in 1954 by Cornelius Tobias and John Lawrence at the Radiation Laboratory (former E.O. Lawrence Berkeley National Laboratory, LBNL). This pioneering work explored the use of hadrons, i.e., protons, deuterons, helium and neon ions, for therapeutic exposure of human patients and concluded at LBNL with the shutdown of the BEVALAC in 1992. Inspired by the success of the early work in the USA, international efforts were made to develop particle therapy into a mature radiological treatment modality where more than 78,275 patients have been treated worldwide with hadron particle therapy. Currently, only protons and carbon ions are in use at particle therapy centers. There are approximately 30 proton facilities in operation, and 5 facilities, worldwide, offering carbon ion particle therapy. To date, more than 56,854 patients have been treated with protons and 7,151 patients treated with carbon ions.

(Statistics courtesy of PTCOG)

Pending regulatory approval for sale in USA.

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LATTICE DESIGN OF A RAPID CYCLING MEDICAL SYNCHROTRON FOR CARBON/PROTON THERAPY*

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Abstract

We present a design of the ion Rapid Cycling Medical Synchrotron (iRCMS) for carbon/proton cancer therapy facility. The facility design, produced at Brookhaven National Laboratory (BNL) at the Collider Accelerator Department (CAD), with Best Medical International, Inc., will be able to treat the cancer patients with carbon, lighter ions and protons. The low energy injector system accelerates ions and protons to the kinetic energy of 8 MeV/u. It consists of a laser driven ion source (for either fully stripped carbon ions or protons), matching solenoid, Radio-Frequency Quadrupole (RFQ) and linac. The 8 MeV beam is injected into a fast cycling synchrotron (iRCMA). The lattice design is a racetrack, with zero dispersion with two parallel straight sections. There are 24 combined function magnets in the two arcs with a bending radius of ~5 meters and maximum magnetic field of B_{max}~1.3 T. The acceleration is performed with a frequency of 15 Hz up to required energy for the treatment with a maximum depth of 27 cm with the spot scanning technique. The maximum energy for carbon ions is 400 MeV/u. Ions are extracted in a single turn and fed to different beam lines for patient treatment.

Introduction

The iRCMS is a state-of-the-art synchrotron design, with the primary parameters listed in Table 1. The present state of the art therapy with the x-rays, Intensity Modulated Radiation Therapy (IMRT), is not as capable of delivering radiation without exit dose as possible with ion beams. The depth-dose curves of proton and light ion beams are inverted from that of x-rays because heavy charged particles give the highest dose near the end of their range in the 'Bragg peak', while significant radiation dose to healthy tissues with IMRT is unavoidable. This design of a fast cycling synchrotron allows for acceleration of both fully stripped carbon ions of 400 MeV/u maximum kinetic energy and protons to a kinetic energy of 320 MeV for radiographic possibilities during treatment. Multiple carbon ion cancer therapy facilities with slow extraction synchrotrons are already fully developed in Japan (Himac in Chiba started in 1994, Gunma University center 2010, and Hyogo 2002) and in Europe (HIT-Heidelberg, Germany and NCAO-Milan-Italy) with more following up in Europe, China and Japan. Carbon ions have a large relative biological effectiveness (RBE) and their Bragg peak is sharp with a small energy loss before reaching the tumor. The higher carbon RBE and the lower energy loss in the patient before reaching the tumor, reduces the overall dose with protons. A clinical facility based on the iRCMS could operate 16 hours per day, 5 days a week, treating to the treatment ~50 patients per day, after build up of patient numbers over 1-2 year period. The primary distinguishing feature of the iRCMS is the rapid cycling oscillation of its magnets, at a frequency of 15 Hz. The electrical circuit of the RCMS main magnets is a resonant type leading to a very stable, simple, and reliable performance. Since the iRCMS cycle is about 100 times faster than other "slow cycling" synchrotrons, the number of protons accelerated per cycle can be as much as 100 times smaller, for a fixed treatment time. This leads to five main advantages: faster energy change, less beam per cycle, efficient beam extraction, better control of delivered dose and a smaller magnet size. With much less beam in the accelerator at any time, there is far less probability for a worst-case incident, in which excess beam is suddenly and inadvertently delivered to the patient. Low beam intensities also avoid the ravages of space charge effects, which at best cause the beam size to increase with intensity, and at worst put a hard limit on the intensity of the beam. Low beam intensities (per cycle) also allow the beam to be extracted from the synchrotron in a single turn of the accelerator, at an energy that can be easily modified from one cycle to the next.

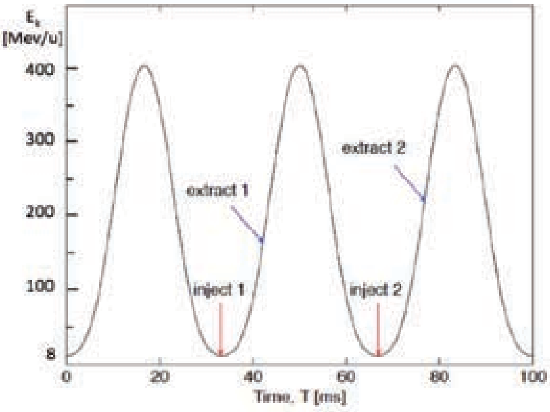

Figure 1: Three cycles of the iRCMS show the energy flexibility. Beam is injected on cycles 1 and 2 ("inject 1" and "inject 2"). The relative timing of the extraction is trivially changed from cycle to cycle, to adjust the extraction energy ("extract 1" and "extract 2").

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Rapid cycling enables the simplicity and robustness of fast extraction, while delivering the ultimate energy flexibility.

Figure. 1 illustrates how the beam extraction energy is adjusted from one synchrotron cycle to the next. Another distinguishing feature of the iRCMS is the strong focusing arrangement of its magnetic optics. Combined with the avoidance of space charge effects, with fast extraction, and with the intrinsically small size of the injected beam, this leads to very small beam sizes. Small beams enable smaller, lighter, and less power-hungry magnets, not only in the synchrotron, but also in the beam transport lines, and (most critically) in the gantries. The iRCMS treatment specifications are presented in Table 1.

Table 1: iRCMS Treatment Specification

Extr. energy $^{12}C^{6+}$/protons @ 27 cm	400–206MeV/u
Min. extract. energy $^{12}C^{6+}$/protons	8 MeV/u
Injection kinetic energy [MeV/u]	8
Repetition rate f_{rep} [Hz]	15
Protons/Gy/voxel (voxel=715 mm^3)	7.5 10^7(46s/Gy/liter)
$^{12}C^6$+/Gy/voxel (voxel=14 mm^3)	9.2 10^4(77s/Gy/liter)

Synchrotron Lattice Design

The racetrack footprint of the synchrotron, consisting of two straight sections and two 180-degree arcs is shown in Figure. 2. Each straight section contains two FODO cells without dipoles and each arc consists of three separated girders, each with two FODO cells made of combined function magnets.

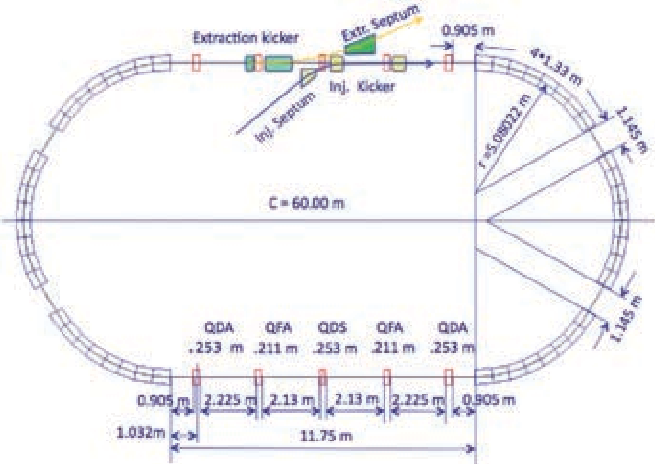

Figure 2: A layout of the synchrotron.

The injector with ion source, solenoid, RFQ, and linac is inside of the synchrotron. The straight sections accommodate: one for injection and extraction, and the other for cavities of the radio frequency (RF) acceleration. Primary physical and optical parameters for the synchrotron are listed in Table 2.

Optics

The dispersion at the entrance and exit points of the arcs is zero, so the straight sections are dispersion free. The dispersion matching in the arcs is performed by choosing suitable values for the quadrupole components of the of the combined function dipole.

Table 2: iRCMS Specification

Circumference [m]	60
Number of FODO cells in the arcs	6
Total number of bends	24
Combined function magnet length [m]	1.33
Quadrupole magnet length [m]	0.25
Horizontal/Vertical tunes	4.84/4.41
Normalized emittance, ε [µm]	0.5
Max. horizontal beta function β_{xmax} [m]	12.16
Max. vertical beta function β_{ymax} [m]	9.44
Maximum Dispersion function D_{xmax} [m]	1.548
Natural horiz./vertical chromaticity, $\varsigma_{x,y}$	-5.3/-5.12
Transition gamma γ_T	4.207

Since the FODO cells in the straight sections are longer than those in the arcs, it is necessary to match the beta functions between the arcs and the straight sections. Due to the symmetry of the lattice displayed in Figure 3, the matching is the same on both sides of the ring.

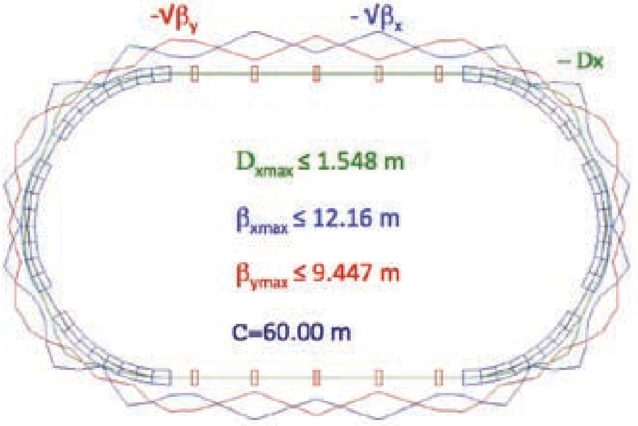

Figure 3: The square root of the horizontal $\sqrt{\beta_x}$ and vertical $\sqrt{\beta_y}$ betatron and the dispersion D_x functions are shown.

The injection and extraction kickers are placed by the horizontal focusing quadrupoles. There are two peaks of the dispersion function. This minimizes the number of power supplies required in the ring. The opposite side straight section has a fast injection kicker and a septum magnet separated from the extraction kicker and a septum magnet. The list of the expected beam sizes, the RF parameters like: the revolution period at the injection/extraction, the revolution frequency for the harmonic number one at the injection/extraction, and other parameters corresponding to injection and maximum extraction energy is shown in Table 3. A new RF system with the harmonic number jump is being considered very seriously.

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Table 3: iRCMS Carbon Ion Specification		
	Injection	Extraction
Kinetic energy [MeV/u]	8	400
Momentum cp/A [MeV]	122.327	951.31
Lorentz β	0.13024	0.71461
Lorentz γ	0.13134	1.429
Maximum rigidity [Tm]	0.8161	6.3472
Bending field [T]	0.1606	1.33
Max. beam $\sigma_{96\%}$ in straights [mm]	2.345	0.308
Max. beam $\sigma_{96\%}$ in the arcs [mm]	4.091	0.537
Revolution frequency [MHz]	0.6507	3.570
Revolution period [μs]	1.5369	0.2801

Closed Orbit Dependence on Momentum

The small dispersion in the arc ($D_{max} \leq 1.5$ m) provides very good momentum dependence as:ww

$$\Delta x = D_x \frac{\partial p}{p} = 1.5 \cdot 0.0023 = 0.00345 \qquad (1)$$

The closed orbit dependence on momentum is shown in Figure 4.

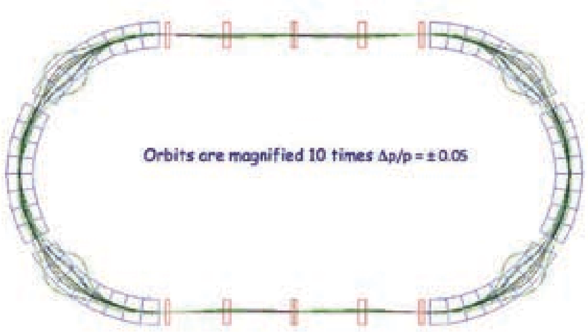

Figure 4: Closed orbit dependence on momentum.

The straight sections due to no dispersion show no beam offsets for the different momentum.

Acceleration Cycle

A single resonant power supply drives synchrotron combined function magnets in series, combining a sinusoidal alternating current of amplitude IAC with a constant direct current IDC so that the total bending magnet current is:

$$I(t) = I_{DC} - I_{AC}\cos(2\pi\, f_{rep} t) \qquad (2)$$

Injection occurs at t = *0*, when the current $I = I_{DC} - I_{AC}$ is at its minimum. A value of the I_{DC} = 1394 A, while the I_{AC} =1050 A. More details on the power supplies are presented at the paper on iRCMS power supplies at this conference (3). Extraction may occur at any time between $t \approx 7$ ms and $t = 16.7$ ms, when the kinetic energy is in the range 96 to 400 MeV. This is illustrated in Figures 1. The bending field in combined function magnets, and the beam momentum are both proportional to the main magnet current (except for small saturation effects). The energy for $^{12}C^{6+}$ and proton beam acceleration is supplied by Radio Frequency (RF) cavities, with a voltage that varies sinusoidally during the acceleration half of the magnetic cycle. All elements in the injector and synchrotron are shown in Figure 5.

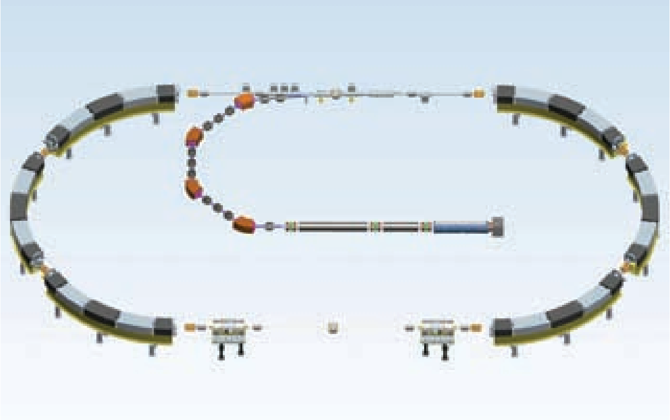

Figure 5. Detail layout of the synchrotron.

Transverse Space Charge

The transverse space charge tune shift ΔQ_{SC} for a round Gaussian beam of *RMS* transverse size σ has a value:

$$\Delta Q_{SC} = -\frac{\lambda r_o R^2}{2Q\beta^2\gamma^3\sigma^2}, \qquad (3)$$

where λ, is the longitudinal line density of protons in the bunch, r_o is classical proton radius, $2\pi R$ is the circumference of the circular accelerator, and Q is the tune without space charge. The space charge limit at which the beam will spontaneously enlarge itself, or suffer losses, is about $\Delta Q_{SC} \approx 0.5$, much larger than the calculated and simulated values of $\Delta Q_{SC} \leq 0.1$. Thus, the RCMS synchrotron operates very comfortably with small beams in a regime far short of the space charge limit, thanks to rapid cycling and consequently low bunch intensities.

Summary

We present the design of a fast cycling synchrotron for a new carbon and proton therapy facility. Conceptual design report of the details, are protected by the Cooperative Research and Development Agreement (CRADA) No.BNL-C-10-03 between Brookhaven National Laboratory and Best Medical International, Inc.

References

[1] S. Peggs et al, "The Rapid Cycling Medical Synchrotron," RCMS" EPAC'02, Paris, p. 2754.