CONCEPTUAL DESIGN OF A HIGH TEMPERATURE SUPERCONDUCTING SPECTROSCOPY-TYPE GANTRY SYSTEM FOR PARTICLE THERAPY

H. Zhao*, M. Fukuda,T. Yorita, H. Kanda, Y. Yasuda, D. Tomono, K. Hatanaka,T. Saitou, S. Morinobu, Y. Morita, K. Takeda, T. Hara, T. Chong, M. Kittaka, S. Matsui, K. Watabe, T. Imura, Research Center for Nuclear Physics (RCNP), Osaka, Japan

Abstract

Radiation therapy is a kind of extremely efficient cancer treatment that uses high doses of radiation to kill cancer cells. In radiation therapy with high energy particles, the dose is usually applied to the tumor with irradiation from several directions, to limit the dose in healthy tissue in vicinity of the tumor. In order to realize a continuous angular range of irradiation, a spectroscopy-type beam delivery device (i.e. the gantry) is proposed. In the conception of spectroscopy-type gantry, beam is guided to the appropriate azimuthal angle with cylindrical magnetic field surrounding the patient, and treatment angles are set by adjusting magnetic strength, instead of rotating a gantry with magnets of the beam transport around the patient. With this conception as well as high temperature superconducting materials, continuous angular range of irradiation could be realized by a super compact spectroscopy-type gantry. In this work, a conceptual design of a high temperature superconducting spectroscopy-type gantry system with a scanning system will be present.

INTRODUCTION

Particle Therapy

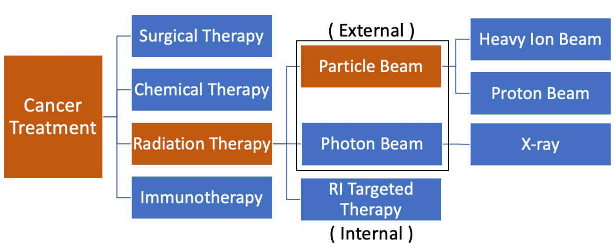

Figure 1: Therapies against cancer.

Radiation therapy (also called therapeutic radiation treatment) is a cancer treatment that uses high doses of radiation to kill cancer cells or slow their growth by damaging their DNA. Cancer cells whose DNA is damaged beyond repair stop dividing or die. When the damaged cells die, the are broken down and removed by the body. Radiation therapy does not kill cancer cells right away. It takes days or weeks of treatment before DNA is damaged enough for cancer cells to die. Then, cancer cells keep dying for weeks or months after radiation therapy ends. Compared to conventional surgical therapy and chemical therapy listed in Fig. 1, radiation therapy gives a lower burden to patient body, and fewer side effects.

Gantry System

In order to acquire multiple treatment angle so that a better dose distribution in the target and better protection of healthy tissue around the target, a design of rotating gantry system is proposed. The rotating gantry system rotates around the patient to get several treatment angle (see Fig. 2), so that the dose in healthy tissue in vicinity of the tumor can be optimized. However, in a rotating gantry system, magnets

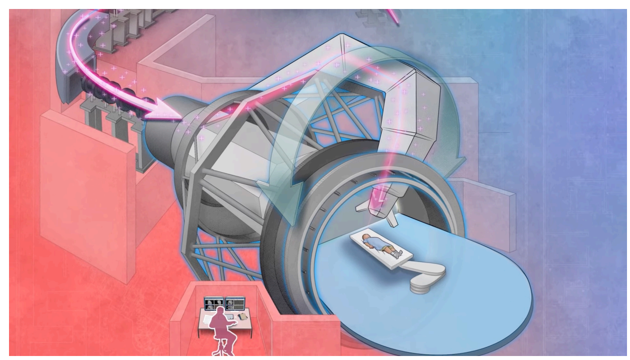

Figure 2: Schematic view of a rotating gantry system, magnets are mounted in gantry rings and rotated with roller assemblies to acquire planned treatment angles. Illustration provided by Johns Hopkins Proton Therapy Center.

are mounted in the gantry structure and rotated with large mechanic arm, making it too huge for many facilities to introduce. The large dimensions (8-12m diameter) and masses (100-200 tons) of the proton gantries [1] limit the rotational speed to 1 turn/min for safety measures preventing possible collisions [2]. Besides, the mechanical system in rotating gantry system also restricts the available treatment angles to several preinstalled ones, which may limit treatment planning in some cases.

PURPOSE

To realize the compactness of gantry system, as well as continuous treatment angles for a better dose distribution, we are designing a HTS (High Temperature Superconducting) Spectroscopy-type Gantry System with pencil beam scanning irradiation. In the HTS Spectroscopy-type Gantry System, no heavy magnets require to be rotated while applying treatment in an arc, allowing a simpler mechanical structure

* zhao@rcnp.osaka-u.ac.jp

and rapid treatment. The purpose of the HTS Spectroscopy-type Gantry System is illustrated in Fig. 3.

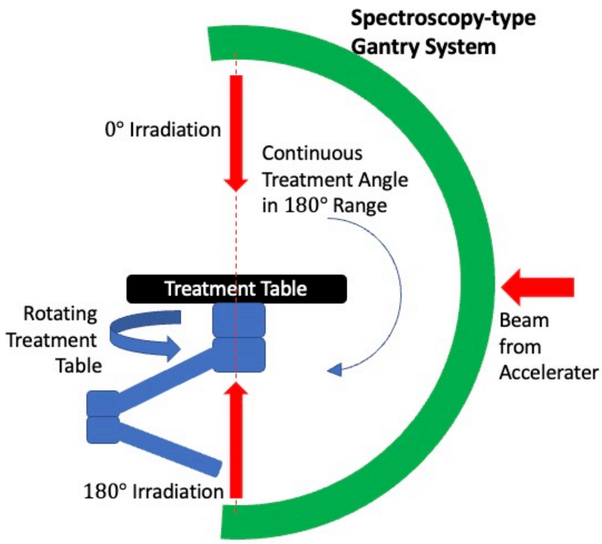

Figure 3: Purpose of a Spectroscopy-type Gantry. Beam are injected from a certain point and transported to a desired treatment angle.

The HTS Spectroscopy-type Gantry System is designed to provide continuous treatment angles in a range of 180° , from the vertical upside (0°Irradiate) to the vertical downside (180°Irradiate). With a rotating treatment table set to 0° or 180°, continuous treatment angles in a range of 360° are actually realizable.

The internal magnetic field strength is estimated to be over 2T, which is hard for common conductor to generate. Therefore, superconducting coils is considered to be necessary for the design. For a better secure operation reliability, which is the most essential point for a medical device, as well as a higher current density in superconducting coil, we decide to use HTS material for the coils.

With spectroscopy-type design and HTS material, this design of gantry system is expected to be super compact comparing to the traditional gantry system.

THEORY

Design Characteristics of Dipole Magnets

A dipole field can be generated, for example, in an electromagnet as shown in Fig. 4 where the beam would travel normal to the cross section into the center of the magnet.The magnetic field B is generated by an electrical current I in current carrying coils surrounding magnet poles. A ferromagnetic return yoke surrounds the excitation coils providing an efficient return path for the magnetic flux. The magnetic field is determined by Ampere's law

$$\nabla \times \frac{B}{\mu_r} = \mu_0 j \tag{1}$$

where μ_r is the relative permeability of the ferromagnetic material and j is the current density in the coils. Integrating

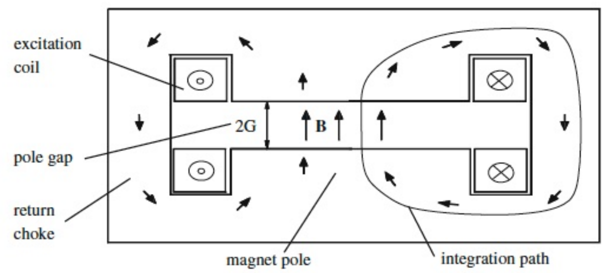

Figure 4: Schematic of cross section of a dipole magnet [3].

Eq. (1) along a closed path like the one shown in Fig. 4 and using Stokes' theorem gives

$$2GB_0 + \int_{iron} \frac{B}{\mu_r} d\sigma = \mu_0 I_{tot} \tag{2}$$

where B_0 is the magnetic field in the center of the magnet aperture between and normal to the parallel magnet poles with a gap distance of $2G$. The integral term in Eq. (2) is zero or negligibly small in most cases assuming infinite or a very large permeability within the magnetic iron. $I_{tot} = 2I_{coil}$ is the total current flowing in the complete cross section of both coils. Solving Eq. (2) for the total current in each coil we get in more practical units

$$I_{coil}(\mathrm{A}) = \frac{1}{0}\mathrm{B}_0(\mathrm{T})\mathrm{G}(\mathrm{m}) \tag{3}$$

which is proportional to the magnetic field and the aperture between the magnet poles.

Particle Beam Guidance

Assuming in general that the magnetic field vector B is oriented normal to the velocity vector v, linear beam dynamics can be restricted to purely transverse fields. The restriction to purely transverse field components has no fundamental reason other than to simplify the formulation of particle beam dynamics. While use a curvilinear coordinate system (x, y, z) following the ideal path, it is necessary to follow a particular particle trajectory for the coordinate s. Then the bending radius for the particle trajectory in a magnetic field is

$$\kappa_{x,y} = \mp \frac{ec}{\beta E} B_{y,x} \tag{4}$$

For multiply charged particles like ions, the electrical charge e in all equations must be replaced by eZ if, for example, ions of net charge Z are to be considered. Since it is also customary not to quote the total ion energy, but the energy per nucleon, Equation (4) becomes for ions

$$\frac{1}{\rho} = 0.2998 \frac{Z}{A} \frac{|B|}{\beta E} \tag{5}$$

where E(GeV/u) is the total energy per nucleon and A the atomic mass.

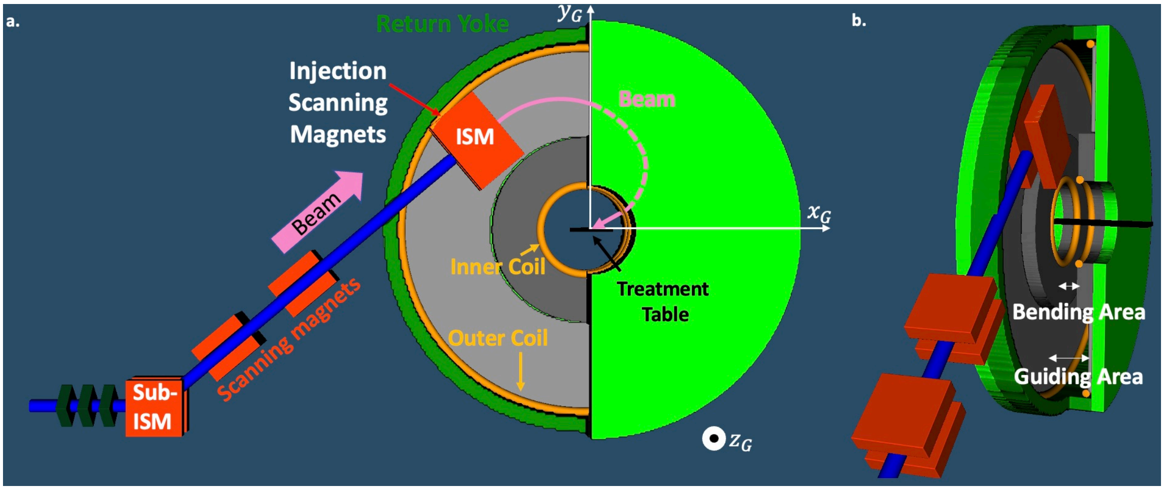

Figure 5: **a.** Front view of designed structure of the HTS Spectroscopy-type Gantry System. Magnets poles for guiding area and bending area are illustrated in light gray and dark gray. Treatment area is within the range of inner coils. **b.** Side view of the structure. Pole gap in bending area and guiding area is designed respectively.

Dispersion Function

The general solution of the equations of motion with higher order parameters then is given by the combination of the two principal solutions of the homogenous part of the differential equation and a particular solution for the inhomogeneous differential equation

$$u(z) = aC_u(z) + bS_u(z) + \delta P_u(z) \tag{6}$$

where the coefficients a and b are arbitrary constants to be determined by the initial parameters of the trajectory. Index u is used to indicate that these functions must be defined separately for $u = x$ and y. A general solution for the equation of motion for any perturbation is derived in Eq. (6), and set $P_u(z) = \delta D_u(z)$,

$$D_u(z) = \int_0^z \kappa_{0u}(\tilde{z})[S_u(z)C_u(\tilde{z}) - C_u(z)S_u(\tilde{z})]d\tilde{z} \tag{7}$$

Beam Sizes

The beam parameters for a Gaussian particle distributions are defined as the standard values of the Gaussian distribution $\sigma_x, \sigma_{x'}, \sigma_y, \sigma_{y'}, \sigma_\delta, \sigma_l$, where most designations have been defined and used in previous chapters and where $\sigma_\delta = \sigma_\epsilon / cp_0$ and σ_l the bunch length. Quoting beam sizes for any particle type in units of σ can be misleading specifically in connection with beam intensities. For example, a beam with a horizontal and vertical size of one sigma has a cross section of $2\sigma_x 2\sigma_y$ and includes only 46.59% of the beam. This is accepted for electron beams with Gaussian distribution but for proton beams intensities are often given for $\sqrt{6}\sigma$'s to cover most of the beam. The fraction of the total beam intensity is compiled for a few generally used units of beam size measurement and for beam size, cross section, and volume. The beam size for Gaussian beams is thereby

$$\sigma_{u,tot}(z) = \sqrt{\epsilon_u \beta_u(z) + \eta^2(z)\sigma_\delta^2} \tag{8}$$

CONCEPTUAL DESIGN OF THE HTS SPECTROSCOPY-TYPE GANTRY SYSTEM

Structure Configuration

The structure configuration of the HTS Spectroscopy-type Gantry System is illustrated in Fig. 5. Treatment table is located at the center of the gantry system. Beam is transported from the left side and injected in the gantry system with an Injection Scanning Magnet (ISM), then guided to the target by the internal magnetic field. Internal magnetic field is separated to 3 areas, guiding area, bending area and treatment area. After injection, beam will be guided to a certain angle in guiding area then bended toward to target in bending area and irradiate the target in treatment area.

Magnetic fields in all area is excited by the outer coils, and the inner coils cancel the magnetic field in the treatment area. Magnetic field in guiding area and bending area is different and adjusted by the pole gap in each area. ISM is used to set treatment angle by bending the beam appropriately during the injection.

Internal Magnetic Field Profile Simulation

The internal magnetic field profile is simulated by Opera3D Simulation Software. For a simpler calculation of particle trajectory, we investigated the magnetic field strength along the radius (r_G) direction, instead of x, y axis. Figure 6 shows the extracted magnetic field profile as a function of radius in the midplane. Then we can calculate the trajectory of single particle.

Particle Trajectory Calculation

With the result of magnetic field profile simulation, now we can calculate the particle trajectory in the gantry system. We start the particle trajectory at the treatment table reversely, and calculated the trajectory through the gantry system to the ISM. With the simulation result in Fig. 6, we

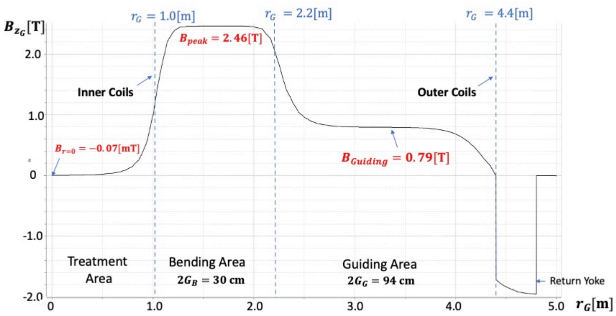

Figure 6: Magnetic field profile in the midplane simulated by OPREA. The peak of B_z in bending area is about 2.46 T. In guiding area, B_z keeps at about 0.79 T.

can solve the equation of motion for a particle at a certain r_G. Therefore, this time we need to use numerical calculation to calculate the particle position change and slope of the trajectory change within a time step change ($\Delta t = 10^{-10}$s). For the approximate calculation, we only considered the 1st order parameter in the equation of motion.

Figure 7 shows the calculated particle trajectory in the midplane of the HTS Spectroscopy-type Gantry System, for treatment angle θ from 0° (vertical irradiation) to 180° (vertical irradiation from the back), using 230MeV protons. Beam is transported to the HTS Spectroscopy-type Gantry System from the left side, and enters the ISM (Injection Scanning Magnet). Magnetic field in the ISM is controlled to direct beam onto the designed trajectory designed for a certain treatment angle θ.

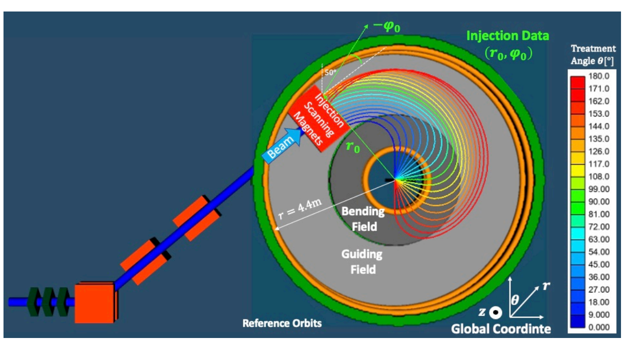

Figure 7: Designed particle trajectory in the midplane of the HTS Spectroscopy-type Gantry System for 0° ~ 180° treatment angle (color bar), using 230MeV protons with numerical calculation.

In order to control the ISM correctly, beam status, such as transportation axis and direction, at the entrance as well as the exit of the magnets are required. The beam status at the entrance mainly depends on the accelerator and beam line adjustment. Therefore, at this phase, we needs to sum up the beam status required at the exit of ISM, to make sure that the beam is transported along the designed trajectory for a certain treatment angle θ. There are 2 necessary injection data for a designed trajectory, which are the distance from the center point of the HTS Spectroscopy-type Gantry System r_0 and the angle between the tangent line of the trajectory and the normal of the ISM φ_0 at the exit of the ISM. Both of the injection data are illustrated in Fig. 7.

When we sum up the injection data (r_0, φ_0) for the treatment angle θ from 0° to 180°, we can get a graph in Fig. 8. The bubble points in Fig. 8 present the injection data for each treatment angle with a changing step of 10° , and the treatment angles between steps are also valid, which can give the injection data for continuous treatment angle in the range of 0° ~ 180°.

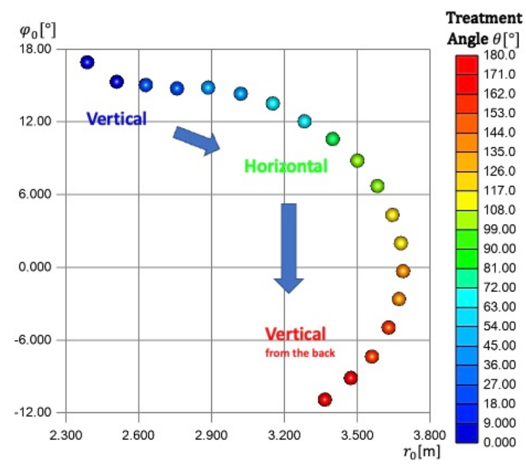

Figure 8: Injection data (r_0, φ_0) for the treatment angle θ with a changing step of 10° from 0° to 180° (color bar). The horizontal axis present the injection data r_0, and the vertical axis is φ_0.

For example in the case of performing horizontal irradiation (θ = 90°), we need to check the injection data (r_0, φ_0) for treatment angle θ = 90° and control the ISM properly to satisfy the required injection data, to direct beam onto the designed trajectory for horizontal irradiation in Fig. 7.

Beam Spot Size Evaluation

The beam phase space changes through a trajectory, thus we need to calculate the phase space changing for each separate trajectory in Fig. 7. Here we will discuss three particle trajectory designed for representative treatment angle 0°, 90° and 180°.

Table 1: Assumed Initial Parameters for Beam Dynamics Calculation

Initial Parameters	
Parameters	Value
ϵ_0	$10^{-6}\pi$·m·rad
β_0	1.0 m
α_0	0
γ_0	1.0 rad
$(\Delta p/p_0)_0$	0.1%
D_0	0 m

Table 2: Calculated Beam Parameters in Bending Plane, Using 230MeV Protons with Constant Emittance $\epsilon = 10^{-6}\pi$·m·rad, and Momentum Deviation $(\Delta p/p_0)_0 = 0.1\%$

Beam Spot Evaluation in Bending Plane					
$\theta[°]$	On Target Phase $(\beta_y, \alpha_y, \gamma_y)$	On Target Dispersion D_y [m]	On Target Beam Spot Size $\sigma_y[mm]$	On Target Derivative y'_{max} [mrad]	Beam Spot Max Size $\sigma_y[mm]$
0	$(1.7, -1.1, 1.3)$	2.3	2.6	1.1	2.6
90	$(13.4, -9.9, 7.4)$	−1.2	3.9	2.7	4.3
180	$(2.6, -2.7, 3.1)$	−4.8	5.1	1.8	6.0

For the calculation, we used 230MeV protons and assumed a beam emittance of 1π·m·mrad, with constant momentum deviation of 0.1% . Twiss parameters are initially set as $\beta_0 = 1.0$mm, $\gamma_0 = 1.0$rad and, $\alpha_0 = 0$. The parameters for calculation is summed in Table 1.

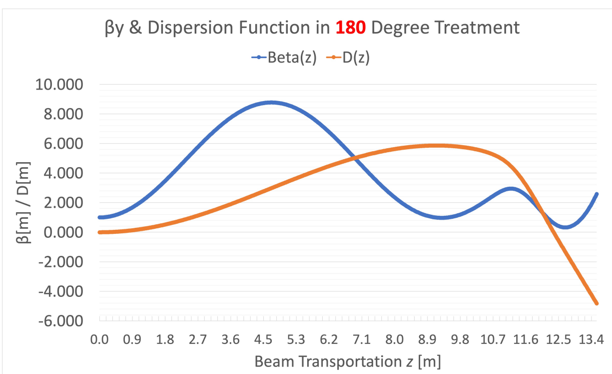

Figure 9: Beam phase parameter β_y and dispersion function D_y in bending plane during transportation for 180° treatment.

Beam Spot Size for 180° Treatment

In order to describe the beam spot size along the particle trajectory in the bending plane caused by both betatron oscillation and momentum dispersion, we need bring β_y and D_y into Eq. (8). Therefore, we graphed the β_y and D_y along the beam trajectory in Fig. 9. The beam phase on target is calculated to be $(\beta_y, \alpha_y, \gamma_y) = (2.6, -2.7, 3.1)$, and a dispersion function of $D_y = -4.8$m.

Then we can observe the beam spot size change during transportation. Initial beam spot size can be calculated with assumed beam emittance and β_{y0} and D_y ,which is $\sigma_{y0} = 1.0$ mm, and increased to $\sigma_y = 5.1$ mm on target. The max beam spot $\sigma_{ymax} = 6.0$ mm size is observed at $z = 10.5$ m.

Apply 0°, 90° 180° Treatment

With the same calculation, we can observe the on target beam spot size for each treatment angle, as illustrated in Table 2. By calculating the beam dynamics in transportation for three typical treatment angle, we know that beam may be defocused in the designed spectroscopy-type gantry system , and a longer particle trajectory gives a stronger beam dispersion, for example 180° treatment. However, in an actual application, a smaller beam spot size usually gives a better dose distribution with pencil beam scanning technology. Therefore, a beam spot size as small as possible is desired in this design. The result with assumed initial beam condition gives us a beam spot with $1\sigma = 5.1$ mm in 180° treatment. A beam spot with this size may be a little hard to create treatment plan with pencil beam scanning, but completely feasible for an actual treatment comparing with practically applied beam spot size, e.g., beam spot size for pencil beam scanning currently applied in HIMAK (Osaka,JP) is $1\sigma = 2 \sim 10$ mm.

SUMMARY

In order to realize the compactness and a continuous treatment angle in a range of 180°, we are designing a HTS(High Temperature Superconducting) Spectroscopy-type Gantry System. In the HTS Spectroscopy-type Gantry System, treatment angle can be set by controlling magnetic field, instead of rotating the beam line around the patient with huge mechanical arms.

In this step of design, we have designed the basic structure configuration and simulated the internal magnetic field profile. With the simulated magnetic field profile, we calculated the particle trajectory and its injection data for a certain treatment angle in a range of 180°, using 1st order in equation of motion. Considering an actual beam transportation system, phase space in beam spot size is also evaluated. With assumed beam emittance and momentum deviation, we calculated the beam spot size changing during the transportation for typical treatment angles. The result indicates that a certain initial phase of beam may defocus on the target, max to $1\sigma = 5.1$ mm in 180° treatment, but still feasible for the actual treatment.

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