

# DESIGN OF THE RCMS LATTICE OPTICS

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## Abstract

The Rapid Cycling Medical Synchrotron (RCMS) is designed to be a very light and inexpensive accelerator. This is possible due to the small beam size that has been chosen early during the design stage. This choice has implications in the design of the lattice optics. In this paper we present an overview of the RCMS optics lattice, the kind of magnets to be used, and also a description of a special optic module that matches the rotating gantry with the rest of the fixed accelerator. Techniques developed to win additional space between quadrupoles without significantly disturbing the lattice functions are also presented.

## 1 INTRODUCTION

The RCMS is a second generation proton therapy synchrotron offering more flexible performance in a simpler lighter and more robust implementation. The RCMS will reduce the typical treatment time and at the same time will reduce the risk of dumping a large amount of radiation into the patient. All of the above is possible thanks to the 4 design choices of the RCMS: strong focusing, rapid cycling, fast extraction, and 7 MeV energy injection.

All 4 choices have associated benefits and challenges that have been studied in detail. In this article attention is focused on the first design choice and the related studies to reduce the cost of the optical lattice of the facility. In general terms, the RCMS is composed of one synchrotron ring, 4 treatment rooms with gantries, and 2 additional room with fixed beam lines (see Figure 1).

The design of all beam lines is based on the strong focusing principle that in contrast with weak focusing leads

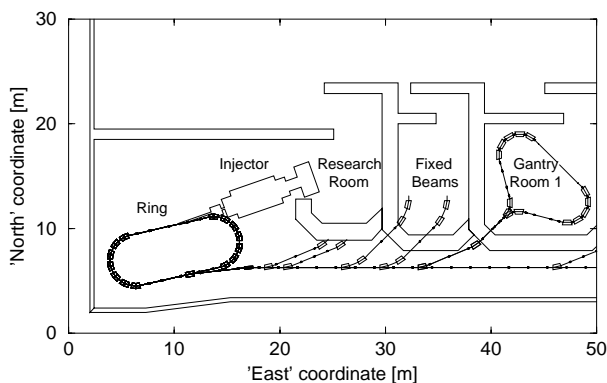


Figure 1: Physical layout of the RCMS. Only 1 gantry room is shown

to a smaller beam size and hence smaller magnets. Strong focusing also makes the optics design much more flexible leaving a lot of room for optimization.

## 2 IBEFUMFO: THE OPTICS DESIGN STRATEGY

Initial versions of the RCMS optic design employed an excessive number of quadrupoles. Also, components like the extraction kicker required a relatively long longitudinal distance. In both cases the idea was to increase the distance between the quadrupoles without increasing significantly the beta functions. Procedures to deal with this problem depend on the specific configuration of quadrupoles and often involve a laborious process of trial and error that not always lead to an optimal solution.

Re-design of the RCMS lattice has been done with the aid of IBEFUMFO (Incoming Beta Function Match to desired FODO cell), a special procedure that allow the optimal choice of either beta functions or distances between quadrupoles for a given requirement [2]

The basic idea of IBEFUMFO is to match the lattice functions of the incoming beam line to a fodo cell with beta functions (at the entrance of the fodo cell) chosen beforehand by the designer. Before doing the matching, it is necessary to know the alpha functions at the entrance of the fodo cell. If the fodo cell starts with a focusing quadrupole the alpha functions just before the quadrupole are related with their respective beta functions by the relations:

$$\alpha_x = \frac{\beta_x}{\sqrt{\beta_x \beta_y}} \quad (1)$$

$$\alpha_y = -\frac{\beta_y}{\sqrt{\beta_x \beta_y}}$$

The half length of the fodo cell 'L' is also fixed once the beta functions are chosen.

$$L = \frac{\beta_x - \beta_y}{\beta_x + \beta_y} \sqrt{\beta_x \beta_y} \quad (2)$$

The matching is generally done by varying the strengths of two quadrupoles inserted between the incoming beam line and the FODO cell and the distances between those two quadrupoles.

## 3 RING OPTICS

The synchrotron ring has two arcs and two straight sections. The arcs are built with combined function magnets

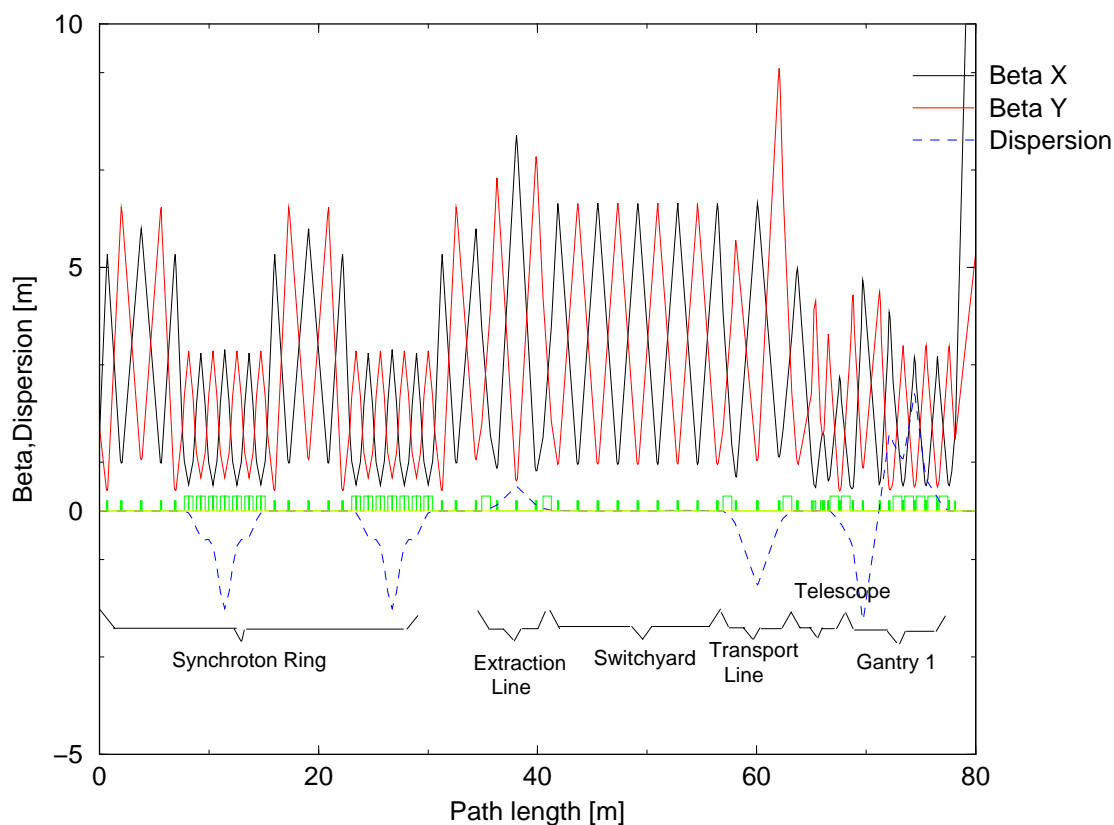


Figure 2: RCMS Lattice Functions

which are dipole magnets with the poles slightly tilted to create a quadrupole component. The number of magnets is a compromise between beam size and cost. More magnets means more quadrupoles in the arc. This leads to smaller beam sizes but more magnets also means a higher cost. Seven dipoles per arc was chosen as the optimal number. Dispersion is made equal to zero outside the arcs by adjusting the strength of the focusing quadrupoles inside the combined function magnets. The defocusing strength and the pole phase rotation of the combined function magnets are used to even vertical and horizontal beta functions. The straight sections should have inter-spaces between the quadrupoles long enough to hold the instrumentation and the accessory components. In particular, it is desirable to have a slot for the extraction septum longer than the distance between the centers of two adjacent combined functions magnets in the arcs. This leads unavoidably to an overall change in the beta functions around the ring unless special matching conditions are imposed in the border of the straight sections and the arcs. The use of IBEFUMFO allows the unavoidable increase of the beta functions in the arcs to be the minimum possible for a given choice of distances between the quadrupoles of the straight sections. As was stated earlier IBEFUMFO can use two quadrupoles to do the matching and a fodo cell structure. The first two quadrupoles of the straight section constitute the two required quadrupoles and the central quadrupole

of the straight section and the spaces at each side of this quadrupole constitute the fodo cell structure. Since arcs and straight sections have mirror symmetry the matching done in one side is equal to the match required in the other side. Also, the straight sections are identical which means that the same power supplies can be used for both straight sections. Only three different quadrupole power supplies are required to do the matching in the whole ring. Since the relations between the length of the fodo cell and the beta functions are known (see Equation 2) it is possible to find the smallest possible value of the maximum beta functions in the straight sections for a given half length fodo cell. The final beta functions of the ring can be seen in Figure 2 under the label "Synchrotron ring".

#### 4 DELIVERY SYSTEM OPTICS

The delivery system is composed of the extraction beam line, the switch yard beam line, the transport beam lines, telescopes, and gantries. The beam is extracted from the synchrotron by a fast kicker followed by a septum magnet. The extraction line comes just after the septum magnet. Since the switch yard is a configuration of fodo cells IBEFUMFO can be directly applied in this case to make the optical matching between the extraction line and the switch yard beam line. The extraction line is designed such that the output lattice functions comply with the equations 2 and also the dispersion is zero outside the extraction line

(see Figure 2).

Since beam lines like the gantries all have identical design it is desirable to have the same beam at the entrance of these beam lines. The switch yard has been designed with this objective in mind as a perfect periodic structure.

The transport lines take the beam from the switch yard to the different rooms of the facility. There are two kinds of transport lines. One of them takes the horizontal beam and bends it 45 degrees. This is mainly used for the gantry rooms. The others takes the beam from the switch yard and bends it 90 degrees. This is used for the fixed beam lines.

The gantry requires axially symmetric optics at the point of rotation. A special optical structure that we have named a telescope has been designed to achieve this objective by making the horizontal and vertical beta function equal at the point of rotation and the alpha functions equal to zero.

The achromatic gantry is built with seven 30 degree dipoles and a reduced number of quadrupole power supplies. Studies of error misalignments (rolls in the dipoles and quadrupole displacements) in the gantry have been made. A total displacement less than 1 mm is expected in the beam aimed to the patient according to this studies.

## 5 MAGNET CONSIDERATIONS

The most recent version of the RCMS uses 4 dipole magnet styles: a chevron dipole which is at the same time a combined function magnet and it is used in the synchrotron ring, a C-type magnet used in the switch yard and transport lines, an H-type rectangular magnet used in the gantry and, an O-type rectangle magnet for the correctors.

Costs decrease with the number of magnet styles. Studies have been done to determine the feasibility of using the synchrotron magnets in the switch yard and the transport lines. That would save the design of the C-type magnets. The switch yard magnet should have enough free space within the iron to allow the beam to go through the magnet when the magnet is off and when the magnet is on as well. Figure 3 shows the beam pipe and the beam itself when the magnet is off (straight beam pipe) and the corresponding pictures when the magnet is off (curved beam pipe) over the magnet iron. The pipes fit exactly within the iron of the synchrotron dipole allowing this dipole to be used as switch yard dipole also.

Similar studies have shown that it is also possible to use a 22.5 degrees synchrotron dipole as a 6.5 degrees dipole which is needed at the extraction line and doesn't fall within the the magnet types described previously.

In summary, the number of style of magnets have been reduced from 4 to 3 which will have a direct impact on the cost of the facility not only in the design stage but also during commissioning and normal operation, since the kinds of replacements needed will be less.

## Trajectories inside Synch Dipole

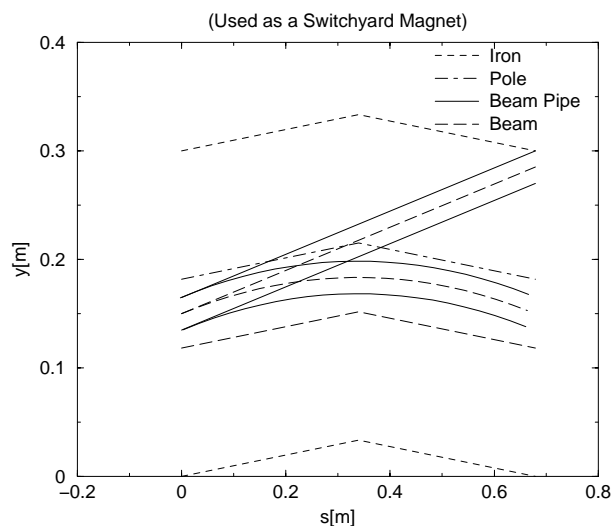


Figure 3: the trajectories and beam pipes of the switch yard magnet within the iron of the synchrotron dipole

## 6 COMPARISONS WITH PREVIOUS DESIGNS

The previous versions of the RCMS used separated magnets for the dipoles and quadrupoles in the arcs of the ring. The inclusion of combined function magnets in the new design has saved sixteen quadrupoles.

Since the cells of the arcs had the same length as the cells in the straight sections in the previous version, the space available for the septum magnet was very reduced leading to a relatively large extraction angles making this system necessarily expensive. IBEFUMFO procedure allowed to increase the space available for the septum magnet from 1.1 meters to 1.8 meters.

The switch yard was also redesigned with the aid of the IBEFUMFO procedure leading to a perfectly periodic structure with a reduced number of quadrupole. The number of quadrupoles in the delivery system went down from 190 quadrupoles to 125 quadrupoles.

## 7 ACKNOWLEDGEMENTS

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