SLOVENSKÁ TECHNICKÁ UNIVERZITA V BRATISLAVE
FAKULTA ELEKTROTECHNIKY A INFORMATIKY

Ing. Jozef Bokor

Autoreferát dizertačnej práce

TRANSPORT OF ION BEAMS IN ROTATING ION-OPTICAL SYSTEMS FOR MEDICAL ACCELERATORS

na získanie akademickej hodnosti doktor (philosophiae doctor, PhD.)

v doktorandskom študijnom programe: **Fyzikálne inžinierstvo**
v študijnom odbore: 5.2.48 Fyzikálne inžinierstvo

Miesto a dátum: Bratislava, 08.08.2016

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Dizertačná práca bola vypracovaná v dennej forme doktorandského štúdia

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ABSTRACT

An ion-optical design of an isocentric proton and carbon-ion gantry with a compact curved superconducting final bending magnet is a major goal of my dissertation thesis. In contrast to other existing designs, "hybrid" beam transport systems containing a single superconducting element – the last bending magnet are presented. All other elements are based on conventional warm technology. Ion-optical properties of such hybrid systems are investigated in case of transporting non-symmetric (i.e. different emittance patterns in the horizontal and vertical plane) beams. Different conditions for transporting the non-symmetric beams are analyzed aiming at finding the most compact gantry versions. The final gantry layouts are presented including a 2D parallel scanning. Matching of the non-symmetric beams to rotating ion optical gantry systems is done by the most modern matching technique – a rotator. The rotator is installed upstream of the gantry and it ensures keeping the input beam parameters (in the gantry co-ordinate system) fixed and independent from the gantry rotation. Design of the rotators that match the ion-optical properties of my final gantry designs is presented as well. The ion-optical and scanning properties of the final gantry designs as well as the ion-optical properties of the rotators are described, discussed and illustrated by computer simulations performed by WinAGILE.

Keywords: Beam optics, Beam transport, Ion therapy, Rotating gantry, Rotator, Superconducting magnet

ABSTRAKT

Hlavný cieľ mojej dizertačnej práce je ióno-optický návrh izocentrickej protónovej a iónovej "gantry"* so supravodivým magnetom. Na rozdiel od iných existujúcich návrhov, v mojej dizertačnej práci je prezentovaný návrh kompaktnej rotačnej gantry založenej na "hybridnom" koncepte, ktorý obsahuje iba jeden supravodivý prvok – konkrétne posledný magnet. Všetky ostatné prvky predstavujú klasické ("teplé") elektromagnety. Ióno-optické vlastnosti týchto hybridných systémov sú prispôsobené pre transport nesymetrických (t.j. rozličné emitancie zväzku v horizontálnej a vertikálnej rovine) zväzkov. V práci sú analyzované rozličné možné vstupné parametre nesymetrických zväzkov na vstupe rotačnej gantry, pre ktoré sú navrhnuté rôzne verzie gantry . Tieto verzie sú vzájomne porovnané z hľadiska ich rozmerov a rozmerov apertúr jednotlivých magnetov. Najkompaktnejšie gantry sú potom považované za finálny variant, v ktorom sú študované systémy 2D paralelného skenovania. Transport nesymetrických zväzkov cez rotačný ióno-optický systém gantry je vyriešený pomocou najmodernejšej metódy, ktorá je založená na tzv. „rotátore". Rotátor je nainštalovaný pred gantry a zabezpečuje, aby vstupné parametre zväzku (v súradnej sústave gantry) boli nemenné a nezávislé od rotácie gantry. Dizertačná práca zahŕňa aj samotný návrh rotátorov. Ióno-optické a skenovacie vlastnosti finálnych návrhov oboch verzií gantry, ako aj ióno-optické vlastnosti rotátorov sú prezentované, diskutované a ilustrované pomocou počítačových simulácií v programe WinAGILE.

Kľúčové slová: optika zväzku, transport zväzku, iónová terapia, rotačná gantry, rotátor, supravodivý magnet

* Pod pojmom „gantry" rozumieme koncovú časť iónovodu, ktorá sa otáča okolo vlastnej osi a umožňuje nasmerovanie zväzku z ľubovoľného smeru na pacienta, ktorý počas ožarovania leží na nastaviteľnom lôžku.

CONTENTS

1 Introduction

Radiotherapy plays an important role in the treatment of cancer. It involves different modalities like brachytherapy, conventional radiotherapy and ion therapy. Conventional and ion therapy are so-called external radiotherapy techniques. The source of radiation is outside the patient. The conventional radiotherapy uses irradiation of the tumor with X-rays or with gamma radiation. In the case of ion therapy, protons and heavy charged-particles like carbon ions are used. Beams of ions, typically $1 \leq Z \leq 6$, represent radiation with favorable physical and biological properties in comparison with photon beams. These favorable physical and biological properties relate to two basic facts about ions. The first one is their specific character of the depth-dose profile that is an inverse one in comparison with photons. It is obvious that photon beams follow almost an exponential decrease (absorption law) whereas particle beams deposit most of energy at the end of their path in matter, at the so-called “Bragg peak” [1]. The second physical advantage of ions heavier than protons is a significantly less influence of multiple Coulomb scattering while penetrating the absorbing medium. That is why, heavy-ion beams are suitable for treating localized deep-seated tumors in the human body and heavy-ion therapy has started developing all over the world. Further details about the radiotherapy are discussed in Ref. [2 - 4].

Nowadays, there is an intensive development of beam delivery systems for heavy ion therapy in the world in order to improve the effectiveness of this cancer therapy as much as possible. The main task of the beam delivery systems is to deliver optimal dose distributions, i.e., delivering a maximum dose to the tumor, and simultaneously, minimizing the dose to surrounding healthy tissue. There are two different basic strategies of beam delivery systems that are in their extreme forms represented as fully passive systems or fully active pencil-beam scanning systems. In the first case, the particle beam is modulated in three dimensions only by passive field-shaping material elements [1] that are put into the beam-path. In the second case, a pencil-like beam scans the whole target volume with the aid of two orthogonal magnetic scanners. There are also hybrid solutions possible combining passive and active beam-delivery techniques.

Modern ion-therapy beam delivery systems shall be based on combination of the pencil beam scanning with rotating gantries. Rotating gantry is a terminating part of the beam line that rotates around the patient in order to allow for delivering irradiation fields from any direction as prescribed by medical doctors. Combination of a rotating gantry with the pencil-beam scanning becomes an ion-optical problem in comparison with the passive systems. The special problem of such ion-optical systems appears in the case of non-symmetric ion beams extracted from a medical synchrotron. The non-symmetric ion beams originate from the resonant slow-extraction technique. Such beams exhibit different emittance patterns and particle distributions in the two transverse (horizontal and vertical) planes [5]. However, the resonant slow-extraction provides the extracted spill duration up to few seconds, offering sufficient time for the active scanning technique [6]. That is why transport and matching of non-symmetric beams in rotating gantries equipped with pencil-beam scanning systems has to be solved.

Transport of the non-symmetric ion-therapy beams in rotating ion-optical systems for medical accelerators is the topic of my dissertation thesis. It is divided into six chapters. The first chapter analyzes the current state-of-the art in modern ion-therapy facilities including an overview of existing systems. The analysis of the current state-of-the art leads to determination of the main goals of the dissertation thesis presented in the second chapter. The third chapter describes the methods chosen to reach these goals. It consists of a short theoretical background concerning the particle dynamics in electromagnetic fields. A basic description of the beam transport code WinAGILE, all simulations have been performed in, is included as well. Design of a proton and carbon-ion gantries with a superconducting final bending magnet as well as their rotator ion-optical systems are presented in the fourth and fifth chapter, respectively. Finally, in the “Results & Discussion” chapter, the achieved results are summarized and discussed.

2 Current State-of-the Art

In two last decades, much progress has been done in the development of sophisticated beam delivery systems in order to improve dose delivery and hence to increase the tumor-control probability. Two different basic strategies can be recognized, namely the passive systems and the active pencil-beam scanning systems. However, there are also many other hybrid solutions that are described in Ref. [7-10]. In the passive systems, the particle beam is adapted in three dimensions to the target volume by passive field-shaping elements. These field-shaping material elements change the beam range, modulate the range, spread the beam laterally and shape its lateral and distal profiles. One has to take into account the secondary effects caused by interaction of the beam with passive field shaping elements in the beam path. Any material in the beam path modifies the beam and causes four main effects: 1. multiple scattering, 2. range straggling, 3. nuclear fragmentation, and 4. neutron production. That is why in modern ion-therapy facilities, there is a trend to develop and use beam delivery systems without any material elements in the beam path, the so-called active (pencil-beam scanning) systems. Active scanning can be defined as the act of moving a charged particle beam and changing one or more its parameters in order to spread the dose deposited by the beam throughout the planned target volume (PTV). The beam size used in active systems is in the order of several millimeters or even a centimeter and such beam is called *the pencil-like beam*. That is why the active systems are usually called as *pencil-beam scanning systems*. In principle, any irregular PTV can be irradiated with much higher dose conformity than in the case of passive systems. It has several advantages. In general, removing the material elements from the beam path significantly reduces beam losses and provides a possibility to minimize secondary effects of the passive systems. Scanning systems can be classified according to the ways in which the beam spot is moved. There are two main types of scanning methods: namely, *spot scanning* and *raster scanning*. More details about spot and raster scanning as well as the other similar methods can be found in Refs. [7, 8, and 10].

For a long time, only two facilities worldwide, Paul Scherrer Institut (later PSI) in Villigen (Switzerland) and Gesellschaft fur Schwerionenforschung (later GSI) in Darmstadt (Germany), have applied pencil beam scanning for tumor therapy. The first PSI spot-scanning system was developed with 200 MeV proton beam in 1992 [11-13]. Further development of this system was implemented later in the PROSCAN project [14-16] for a new isocentric proton gantry at PSI (the second gantry generation at PSI). Another fully active 3D scanning beam system was developed in the early 1990s at GSI and was finally implemented at the heavy-ion therapy unit at the clinic in Heidelberg [17, 18]. Compared to the PSI system, a raster scanning concept was followed. Benefiting from the GSI pilot project, the first clinical irradiation facility for heavy ions in Europe, the Heidelberg Ion-Beam Therapy Center (HIT, Germany), was built. Once it was fully operational and running at full capacity, starting in 2013, roughly 750 patients are treated per year [19]. Nowadays, there are more new facilities for heavy-ion cancer-therapy using pencil beam scanning in the world, especially in USA (protons) and Japan (protons, ions) [20 - 23]. A complete list of such facilities all over the world, in operation or under construction, is available online on the website of the Particle Therapy Co-Operative Group (PTCOG).

Except of the active scanning systems, development of rotating ion gantries belongs to the main trends in modern ion therapy facilities in the world. Rotating gantry is a terminating part of the beam line. It can rotate 360° around the horizontal axis, which allows irradiating the tumor from any side, as it is routinely done with conventional radiotherapy LINACs (Linear Accelerators). A common gantry layout starts with deflecting the beam away from the axis and then bending it back to the patient. In principle, all gantry concepts can be classified into two basic categories: *isocentric* and *exocentric* gantries. The most straightforward technical concept of rotating gantries and moreover preferred by the medical community as an optimal gantry concept is the isocentric one. In this case, the rotatable patient couch is installed in the gantry isocenter that lies on the axis of the gantry rotation. The patient position is fixed on the patient table and the whole rotatable patient couch is able to perform 2π-rotation around the vertical axis. Typical arrangement of the isocentric gantry is shown in the following Fig. 2.1.

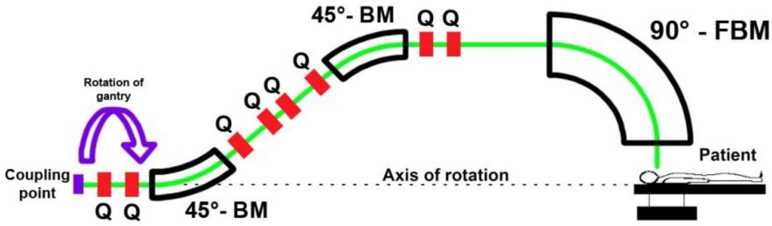

Fig. 2.1: Typical configuration of an isocentric gantry. BM – bending magnet (dipole), FBM – final bending magnet, Q – focusing magnet (quadrupole). The gantry is shown in its top position.

In the case of the rotating gantries, the main technical problems are caused by their overall size and weight. Commonly used proton gantries are about 8 – 10 m long and have about 200 t [5, 12, 14-16]. The situation is much more complicated in the case of heavy-ion therapy. For heavy ions (e.g. carbon ions), the gantry must be significantly larger. The maximum carbon ion energy used for treatment is ~ 440 MeV/u corresponding to the beam rigidity of 6.74 Tm, which leads for conventional magnets to a bending radius of more than 3 m. That is why the use of normal-conducting dipole technology produces a gantry ≈ 20 m in length and nearly ≈ 15 m in diameter with an overall mass of 600 t [2, 24-26]. One can see that such a gigantic construction cannot be a standard hospital-based device. Therefore, recent development of ion therapy gantries is mainly focused on new alternatives in order to reduce the overall gantry size. One possibility could be a superconducting gantry using superconducting magnets, at least the last one. This is a main idea of my dissertation thesis.

The size and weight of heavy ion gantries are primarily determined by the large aperture of the final bending magnet (later FBM). A way how to reduce the heavy-ion gantry size and weight is to replace the conventional FBM with a compact high-field superconducting bending magnet. Currently, first studies show that high-field superconducting magnets can be constructed in compact dimensions using Canted Cosine-Theta designs [27-34]. By now, the only one superconducting rotating gantry for heavy-ion therapy has been built in Japan [35-37]. Commissioning of this gantry was completed in October 2015 and the first patient treatment is planned in 2016. The length and radius of this isocentric gantry is approximately 13 m and 5.5 m, respectively. The gantry optics is matched for transporting the carbon-ion beams at the maximum energy of 430 MeV/u [35]. However, it still assumes a symmetric carbon-ion beam at the entrance of the gantry, which is supposed to be achieved with a scattering foil with variable thickness. Hence, the gantry optics is not matched for transporting the non-symmetric ion beams that are expected to appear from medical synchrotrons using the 3rd order resonance slow extraction [38, 39].

The non symmetric ion beams are meant as beams with different emittance patterns and particle distributions in two transverse (horizontal and vertical) planes [5]. If the beam at the coupling point, the point where the fixed beam line is connected to the rotating gantry, is not rotationally symmetric, the input beam parameters "seen" by the gantry coordinate system become a function of the angle of gantry rotation. This dependence, unless special precautions are applied, is transformed also to the output beam parameters at the gantry exit [40]. That is why this dependence should be eliminated in order to achieve rotationally independent transport of the beam by the rotating gantry. There are several ways how to eliminate the dependence of the output beam parameters on the gantry angle. Generally, they can be classified into two basic strategies [5, 41]. The first strategy is that the ion optical setting of the rotating beam line fulfills special ion optical constraints imposed upon the beam transport system of the gantry. This strategy has been invented in GSI Darmstadt [5, 40] and is called *"the sigma matrix matching"*. The second strategy is based on eliminating the angular dependence of the beam parameters at the gantry entrance, in other words, the input beam parameters are "rotated" together with the mechanical rotation of the gantry. This method has been proposed by the PIMMS group and is called *"the rotator matching"* [42-46]. There are also some other proposals, e.g. the emittance balancing technique [47-49], which is principally similar to the rotator method, or using a thin scatterer upstream of the gantry entrance [50, 51].

3 Dissertation Theses

According to the current state-of-the-art in modern ion therapy, the dissertation theses are specified as follows:

1. *To review existing superconducting magnet design studies and to select suitable candidates for ion-therapy gantries.*
2. *To design an ion-optical system for a compact proton gantry equipped with a pencil beam scanning system using a state-of-the-art superconducting magnet.*
3. *To design an ion-optical system for a compact carbon-ion gantry equipped with a pencil beam scanning system using a state-of-the-art superconducting magnet.*
4. *To optimize the above mentioned gantry designs from the point of view of gantry compactness.*
5. *To design and optimize rotators for the proton and carbon-ion gantries.*

The major goals of my dissertation thesis represent ion-optical designs of the isocentric compact rotating gantries for proton as well as carbon-ion therapy. A new feature is incorporation of a superconducting bending magnet to the gantry beam-transport system. In contrast to other existing designs, it is a “hybrid” beam-transport system containing a single superconducting element – the last bending magnet. All other elements are based on conventional warm technology. The parameters of the last superconducting bending magnets are based on real prototypes. Recently, first design-studies of such superconducting bending magnets have been published [27-34], which opens the possibility to design a new type of the compact superconducting gantry. The final gantry layouts are presented including a 2D parallel scanning. The preferred positioning of the scanning magnets is upstream of the final bending magnet, which significantly minimizes the gantry radius and reduces a volume of the mechanical gantry supporting-structure. Ion-optical properties of the rotating gantries are investigated in case of transporting the non-symmetric beams. Different conditions for transporting the non-symmetric beams are analyzed aiming at finding the optimal, i.e. the most compact, gantry version. Such a hybrid beam transport system for transport of non-symmetric beams and 2D parallel pencil-beam scanning is designed for the first time. The ion-optical design of the gantry is realized by computer simulations performed in WinAGILE.

The analysis of possible matching techniques for transporting of the non-symmetric ion beams in rotating ion-optical systems was necessary to select the gantry concept used for my superconducting gantry design. In the early design phase, I have concentrated on the gantry optics without having to fulfill additional ion-optical constraints, as it is necessary for the sigma-matrix matching. Using the scattering foil has specific drawbacks [38, 39]. Transporting the non-symmetric beams through the rotating gantry is another option [42-49] that I have selected for my gantry designs. It is based on the rotator matching technique. In consequence of that, my dissertation thesis deals with a design of the rotators, too. Using a rotator may also help in reaching more compact and lighter gantry version. Design of the rotators is made with the aid of WinAGILE, too.

4 Instruments and Methods

4.1 WinAGILE – WINdows Alternating Gradient Interactive Lattice dEsign

The beam dynamics simulations as an inevitable part of the design of any beam-transport system were performed in the beam transport code WinAGILE. WinAGILE is dedicated to the interactive design of alternating-gradient lattices for synchrotrons and transfer lines [52]. It is particularly suited to professional design work concerning small and medium-sized rings and transfer lines. All simulations are realized in an interactive lattice-design mode that is supported by numerical matching routines. There are several routines for designing coupling compensation schemes [53]. One extra feature is the calculation of sections of transfer lines that rotate around their axis. This is basically a coupling problem that has been included for the design of the rotating gantries and rotators for ion therapy facilities. A lattice usually consists of many elements that can be magnetic, electrostatic or electromagnetic. WinAGILE includes a wide spectrum of these ion-optical elements like drift space, dipole magnet, quadrupole, sextupole, multipole, solenoid, radio-frequency cavity, etc. All of these elements are defined in WinAGILE by their transfer matrices. The transfer matrix – $\mathbf{M}$ is generally a square 6×6 matrix. The beam transport-line usually represents a sequence of individual ion-optical elements. Hence, the overall transfer matrix of the entire beam transport-line consisting of n elements with individual transfer matrices $\mathbf{M_1}$, $\mathbf{M_2}$, …., $\mathbf{M_n}$ is:

$$\mathbf{M}_{\mathbf{over}} = \mathbf{M}_{\mathbf{n}}\mathbf{M}_{\mathbf{n-1}}.....\mathbf{M}_{\mathbf{2}}\mathbf{M}_{\mathbf{1}} \tag{1}$$

for particles entering the system at the element number “1” and leaving the system at the element number “n” [5]. Calculation of the particle motion is performed by the first order matrix multiplication (single-particle formalism):

$$\mathbf{Y}_{\mathbf{out}} = \mathbf{M}_{\mathbf{over}}\mathbf{Y}_{\mathbf{in}} \tag{2}$$

where $\mathbf{Y}_{\mathbf{out}}$ and $\mathbf{Y}_{\mathbf{in}}$ are particle vectors containing the particle coordinates at the exit and at the entrance of the beam transport-line, respectively. Generally, the beam consists of zillions of particles [5] and it is also possible to calculate the beam envelope as a collective result of the transport of all individual particles. The beam-envelope formalism is based on the beam representation in the six-dimensional phase-space by a six-dimensional ellipsoid. The beam transport (without beam losses) looks in the phase-space like a transformation of the shape of the ellipsoid while keeping its volume constant. The ellipsoid in the phase-space is characterized by “the beam sigma-matrix” – $\boldsymbol{\sigma}$**.** The first-order matrix transformation that is used to calculate the beam parameters along the beam line is:

$$\boldsymbol{\sigma}_{\mathbf{2}} = \mathbf{M}_{\mathbf{over}} \cdot \boldsymbol{\sigma}_{\mathbf{1}} \cdot \mathbf{M}_{\mathbf{over}}^{\mathbf{T}} \tag{3}$$

where $\boldsymbol{\sigma}_{\mathbf{1}}$ and $\boldsymbol{\sigma}_{\mathbf{2}}$ are real, positive definite, symmetric beam sigma matrices at the entering position “1” and at the exit position “2” of the beam line, respectively; and $\mathbf{M}_{\mathbf{over}}^{\mathbf{T}}$ is a transpose of the transfer matrix $\mathbf{M}_{\mathbf{over}}$. Transformation (3) allows calculating the beam sigma-matrix and hence all ion-optical beam parameters at any position along the beam line. Further theory concerning the single-particle formalism and the beam-envelopes transformations can be found in Refs. [5, 54, 55].

The beam sigma-matrix in WinAGILE is expressed in terms of the TWISS parameters β, γ and α:

$$\boldsymbol{\sigma} = \varepsilon\begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix} \tag{4}$$

where β is in [m] and is related to the beam size; γ is in [m^{-1}] and is related to the beam divergence; dimensionless correlation term α reflects the tilt of the ellipse in the 2D phase space (i.e. the correlation between particles' position and angle) and ε is the beam emittance defined as:

$$\varepsilon = \frac{A}{\pi} = \sqrt{\|\boldsymbol{\sigma}\|} \tag{5}$$

where A is the area of the beam ellipse in the phase space for one transverse plane.

4.2 Matching of Rotator-Matrices

Ion-optical properties of the designed gantries were investigated in case of transporting non-symmetric beams. There are several possibilities of transporting the asymmetric beams in rotating ion-optical systems [5, 40, 42-51]. However, the design philosophy in my dissertation thesis requires keeping the input beam-parameters (in the gantry co-ordinate system) fixed and independent from the gantry rotation. That is why I decided to investigate gantries that are going to be combined with a rotator. This is the most advanced technique for matching the non-symmetric beams to rotating ion-optical systems. It makes it possible to profit from a low beam-emittance in one of the gantry transverse planes. Furthermore, it also relaxes the ion-optical constraints imposed on the gantry and makes the whole system more flexible (leading for example to a modular architecture [6]) and compact. According to my experience, an effective strategy for matching and optimizing of the rotator transfer matrices is based on the TWISS formalism implemented in WinAGILE.

If there is no coupling between the horizontal and vertical transverse planes, the transfer sub-matrices can be written in terms of the TWISS parameters as follows:

$$\mathbf{M}_{\mathbf{ROT}}^{x,z} = \begin{pmatrix} \sqrt{\frac{\beta_2^{x,z}}{\beta_1^{x,z}}}\cos\mu^{x,z} + \alpha_1^{x,z}\sin\mu^{x,z} & \sqrt{\beta_1^{x,z}\beta_2^{x,z}}\sin\mu^{x,z} \\ \frac{(\alpha_1^{x,z}-\alpha_2^{x,z})\cos\mu^{x,z}-(1+\alpha_1^{x,z}\alpha_2^{x,z})\sin\mu^{x,z}}{\sqrt{\beta_1^{x,z}\beta_2^{x,z}}} & \sqrt{\frac{\beta_1^{x,z}}{\beta_2^{x,z}}}\cos\mu^{x,z} - \alpha_2^{x,z}\sin\mu^{x,z} \end{pmatrix} \tag{6}$$

where index "1" and "2" refers to the entrance and the exit of the rotator, respectively, index "x" and "z" refers to the horizontal and vertical plane, respectively and μ is the phase advance:

$$\mu = \int_1^2 \frac{1}{\beta(s)}\,ds \tag{7}$$

where s is the longitudinal coordinate along the design orbit.

In order to simplify the matching strategy, I set in both transverse planes α_1=0 and asked WinAGILE to match α_2=0, too (waist-to-waist). With this simplification and taking into account that the vertical rotator sub-matrix has to be "an opposite-sign mirror" of the horizontal rotator sub-matrix, the following relations must hold for the rotator transfer matrix:

$$\sqrt{\frac{\beta_2^x}{\beta_1^x}}\cos\mu^x = -\sqrt{\frac{\beta_2^z}{\beta_1^z}}\cos\mu^z \tag{8}$$

$$\sqrt{\beta_1^x\beta_2^x}\sin\mu^x = -\sqrt{\beta_1^z\beta_2^z}\sin\mu^z \tag{9}$$

$$-\frac{\sin\mu^x}{\sqrt{\beta_1^x\beta_2^x}} = \frac{\sin\mu^z}{\sqrt{\beta_1^z\beta_2^z}} \tag{10}$$

$$\sqrt{\frac{\beta_1^x}{\beta_2^x}}\cos\mu^x = -\sqrt{\frac{\beta_1^z}{\beta_2^z}}\cos\mu^z\,. \tag{11}$$

I have recognized three possibilities to match the above constraints leading to three different types of rotators. The first type is **a point-to-point imaging lattice**. The point-to-point imaging lattice is characterized by the transfer matrix terms $r_{12} = r_{34} = 0$. The relations (8 - 11) translate into the following set of constraints:

$$\sqrt{\frac{\beta_2^x}{\beta_1^x}}\cos\mu^x = -\sqrt{\frac{\beta_2^z}{\beta_1^z}}\cos\mu^z \tag{12}$$

$$\sin\mu^x = \sin\mu^z = 0\,, \tag{13}$$

which can be satisfied, if the phase advance is an integer multiple of π and the horizontal and vertical phase advances are shifted by π with respect to each other. The beta functions must satisfy the condition:

$$\frac{\beta_2^x}{\beta_1^x} = \frac{\beta_2^z}{\beta_1^z} \tag{14}$$

The second type of the rotator is **a parallel-to-point imaging lattice**. The parallel-to-point imaging is characterized by the transfer matrix terms $r_{11} = r_{33} = 0$. The relations (8 - 11) translate into the following set of constraints:

$$\cos\mu^x = \cos\mu^z = 0 \tag{15}$$

$$\sqrt{\beta_1^x\beta_2^x}\sin\mu^x = -\sqrt{\beta_1^z\beta_2^z}\sin\mu^z \tag{16}$$

which can be satisfied, if the phase advance is an integer multiple of $\pi/2$ and the horizontal and vertical phase advances are again shifted by π with respect to each other. Because of the smaller phase advance, a structure shorter than the point-to-point imaging lattice should be expected. The beta functions must satisfy the condition:

$$\beta_1^x\beta_2^x = \beta_1^z\beta_2^z\,. \tag{17}$$

The third type of the rotator is **a general rotator lattice**. In a general case, the relations (8 - 11) translate into the following set of constraints:

$$\sqrt{\frac{\beta_2^x}{\beta_1^x}}\cos\mu^x = -\sqrt{\frac{\beta_2^z}{\beta_1^z}}\cos\mu^z \tag{18}$$

$$\sqrt{\beta_1^x\beta_2^x}\sin\mu^x = -\sqrt{\beta_1^z\beta_2^z}\sin\mu^z \tag{19}$$

which can be satisfied, if the horizontal and vertical phase advances are shifted by π with respect to each other and the beta functions satisfy simultaneously the conditions:

$$\sqrt{\frac{\beta_2^x}{\beta_1^x}} = \sqrt{\frac{\beta_2^z}{\beta_1^z}} \tag{20}$$

$$\sqrt{\beta_1^x\beta_2^x} = \sqrt{\beta_1^z\beta_2^z} \tag{21}$$

Solving the conditions (20) and (21) yields:

$$\beta_1^x = \beta_1^z \cap \beta_2^x = \beta_2^z, \tag{22}$$

which means that one has to set identical input beta functions in the two transverse planes and match identical output beta functions in both transverse planes as well. The input and output beta functions need not to be identical.

There are two essential features of this fitting strategy: (a) the fitting is done assuming the waist-to-waist imaging, and (b) the horizontal and vertical phase advances are shifted by π with respect to each other. This provides a good compromise between the complexity and flexibility of the ion-optical design. The waist-to-waist condition makes the terms of the transfer matrix sin-like or cos-like functions of the phase advance. This can be used for the necessary sign-inversion between the horizontal and vertical sub-matrices of the rotator transfer matrix simply by shifting the horizontal and vertical phase advances by π with respect to each other. This simplifies the associated constraints on the beta functions. Despite this simplicity, different types of the rotators can be designed in order to find the most compact version. Further details concerning the matching of rotator matrices are discussed in Ref. [56].

5 Summary of Achieved Results and Discussion

An ion-optical design of the proton as well as carbon-ion rotating gantry with superconducting final bending magnet was done. The magnet parameters that are based on real magnet prototypes were adopted from the literature. Although – according to the communication with the magnet designers – there is a possibility to tune some magnet parameters (e.g. the gradient of the magnetic field), I assumed these parameters to be fixed. It also means that the ion-optical properties of the final bending magnet were considered to be fixed. My role was to design the rest of the gantry beam transport system that fitted into the ion-optical properties of the superconducting magnet. At this occasion, a systematic case-study of several gantry versions has been performed and the most compact solutions were selected as the final proton and carbon-ion gantry designs. Different conditions for transporting the beams were analyzed aiming at finding the most compact gantry version. Three major cases, namely "an equal input beam-size", "an equal input beam-divergence", and "an equal input beta function" were investigated. Beam waists in both transverse planes at the gantry entrance were assumed. Each case was sub-divided into two situations: (a) the bigger emittance was in the horizontal plane of the gantry, and (b) the bigger emittance was in the vertical plane of the gantry.

5.1 Proton Gantry Design

The most important specifications that were used for designs of my proton gantry are listed as follows:

1. Isocentric configuration;
2. Overall gantry size as small as possible;
3. Minimum drift space from the gantry exit to the isocenter 1.2 m;
4. Double-achromatic beam optics;
5. Beam waists at the isocenter;
6. Reference output beam size at the isocenter 4 mm (FWHM);
7. Beam rigidity 2.219 Tm (limited by the SC-magnet design). This rigidity corresponds to ~ 212 MeV/u p^+ with penetration range in water of 28 cm;
8. Upstream and parallel scanning in both directions (the upstream scanning reduces the gantry radius and the parallel scanning mode has been foreseen in the design of the superconducting final bending magnet [30, 31]).

The scheme of the conceptual gantry layout is visualized in Fig. 5.1. The major goal was to obtain a minimal overall size of the gantry. It was primarily reached by a theoretical minimum of the gantry radius. Further optimization of the gantry beam-transport system allowed for further reduction in the gantry length.

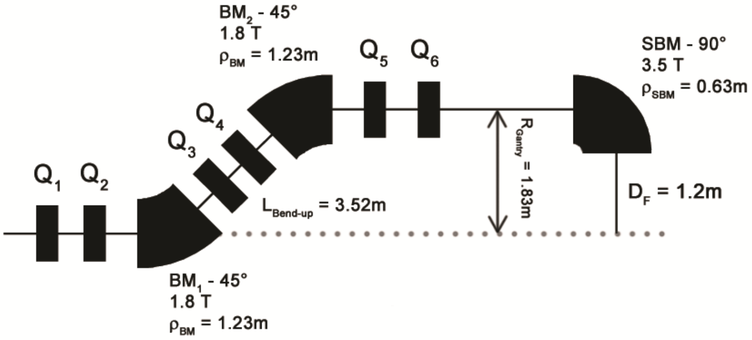

Fig. 5.1 Scheme of the initial proton gantry setup.

I have chosen the combined-function 3.5 T superconducting magnet [30, 31] as the final bending magnet for my proton gantry. The coil of this magnet is curved 90° at a radius of 634 mm. Magnet has 130 mm clear bore. The gantry optics is matched to ion-optical properties of this superconducting magnet. The input beam parameters were assumed to be non-symmetric with a beam emittance of 23.1π mm.mrad and 4.1π mm.mrad in the horizontal and vertical plane, respectively [57].

The most compact gantry version has been designed for the equal input beta functions of 2 m with the bigger beam emittance in the vertical gantry plane. The corresponding gantry layout is shown in Fig. 5.2. The ion-optical settings of this final proton gantry version are listed in Table 5.1. The lattice functions are plotted in Fig. 5.3 (left panel), whereas the right panel shows the beam envelopes.

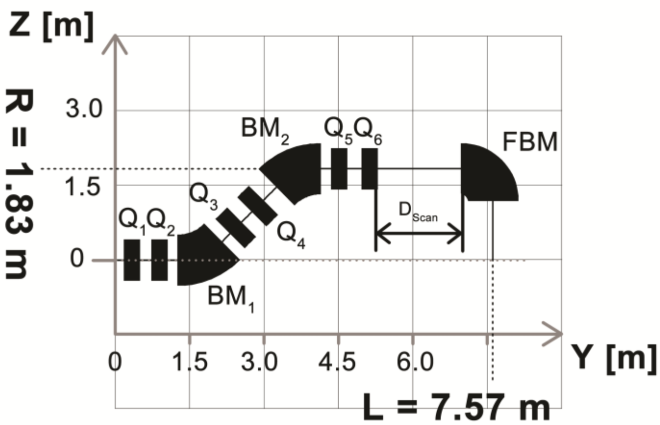

Fig. 5.2 Layout of the final proton gantry version with equal input beta-functions of 2.0 m (the vertical plane of the gantry receives the bigger beam emittance). R – gantry radius, L – gantry length, BM_i – bending magnets (dipoles), FBM – final bending magnet, Q_i – quadrupole magnets, D_{Scan} – drift for a scanning system.

Table. 5.1 The gantry settings corresponding to the proton gantry layout in Fig. 5.2. The following abbreviations are used: d = drift length, L_{eff} = effective length of a quadrupole, A_p = quadrupole half-aperture, B = magnetic flux density on the quadrupole pole tip ("+" for vertical focusing), B_{BEND} = magnetic flux density of the dipole magnet, B_{QUAD} = 1st order magnetic field gradient (quadrupole term), B_{SEXT} = 2nd order magnetic field gradient (sextupole term). The WinAGILE sign convention for magnetic field components is applied [58].

Element	Physical and magnetic parameters		
Drift	$d = 0.15$ m		
Quadrupole 1	$L_{eff} = 0.30$ m	$A_p = 7.0$ cm	$B = +0.981$ T
Drift	$d = 0.25$ m		
Quadrupole 2	$L_{eff} = 0.30$ m	$A_p = 7.0$ cm	$B = -0.863$ T
Drift	$d = 0.23$ m		
45° Bending magnet 1	$B_{BEND} = 1.8$ T		
Drift	$d = 0.26$ m		
Quadrupole 3	$L_{eff} = 0.30$ m	$A_p = 7.0$ cm	$B = +0.997$ T
Drift	$d = 0.32$ m		
Quadrupole 4	$L_{eff} = 0.30$ m	$A_p = 7.0$ cm	$B = -0.835$ T
Drift	$d = 0.40$ m		
45° Bending magnet 2	$B_{BEND} = 1.8$ T		
Drift	$d = 0.23$ m		
Quadrupole 5	$L_{eff} = 0.30$ m	$A_p = 7.0$ cm	$B = +0.997$ T
Drift	$d = 0.32$ m		
Quadrupole 6	$L_{eff} = 0.30$ m	$A_p = 7.0$ cm	$B = -0.920$ T
Drift for the scanning system	$d = 1.70$ m		
90° final bending magnet	$B_{BEND} = 3.5$ T	$B_{QUAD} = +3.17$ T/m	$B_{SEXT} = -1.84$ T/m^2
Drift to the patient	$d = 1.20$ m		

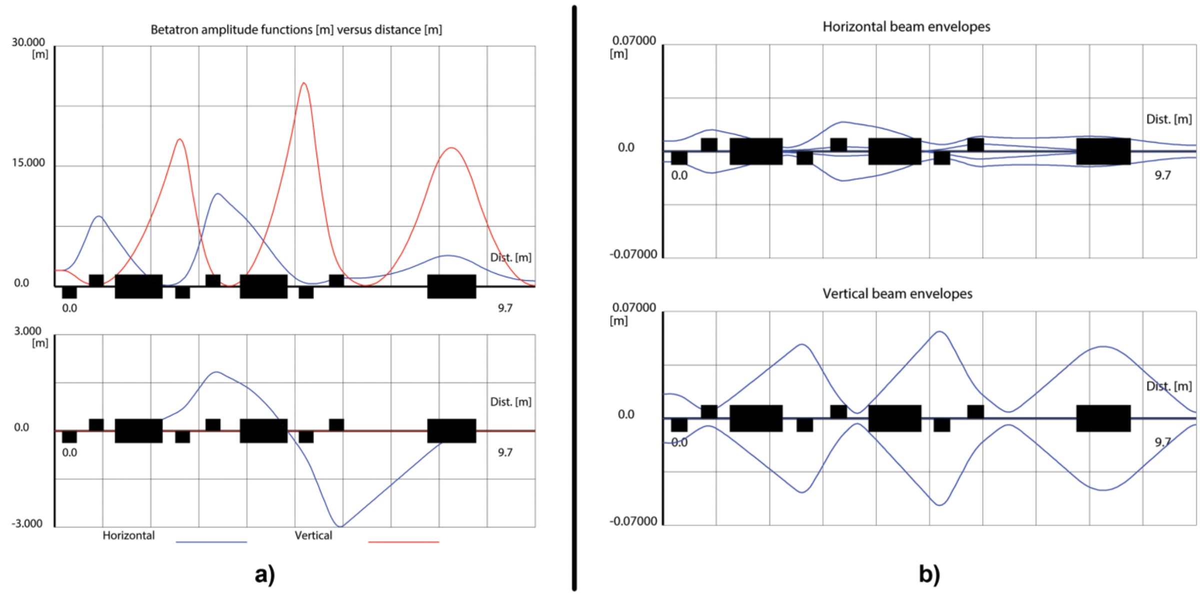

Fig. 5.3 a) Beta functions (upper) and dispersion functions (lower) in the horizontal (blue) and vertical (red) plane. b) Horizontal (upper) and vertical (lower) beam envelopes in terms of FWHM. The black boxes indicate the gantry magnets.

The length and radius of this gantry is 7.57 m and 1.83 m, respectively. The beam-line aperture can be reduced approximately by a factor of 2 in comparison with other proton gantries, see Fig. 5.4. It shows horizontal and vertical beam envelopes inside all proton gantry versions in terms of FWHM. The volume occupied by this proton gantry is only 67 m^3. The length and radius of the LBNL/PSI superconducting proton gantry designed and published by Weishi et al. [59] in 2015 is 8.3 m and

2.5 m, respectively, which corresponds to the volume of 155 m^3. Even the concept of this gantry is significantly different comparing with my, I have chosen it as the state-of-the-art for superconducting proton gantries in order to make an appropriate comparison. The optics of the LBNL/PSI gantry is not matched for transporting non-symmetric proton beams. Fig. 5.5 shows 3D sketches of my proton gantry with the superconducting final bending magnet designed by Caspi et al. [30, 31], and the LBNL/PSI superconducting proton gantry [59]. No mechanical design has been done for the LBNL/PSI and my gantries. That is why no data concerning the gantries` weight are available at the moment in order to make a comparison. However, one can say that the hybrid beam transport system with the single superconducting final bending magnet holds promise for significant reduction in weight.

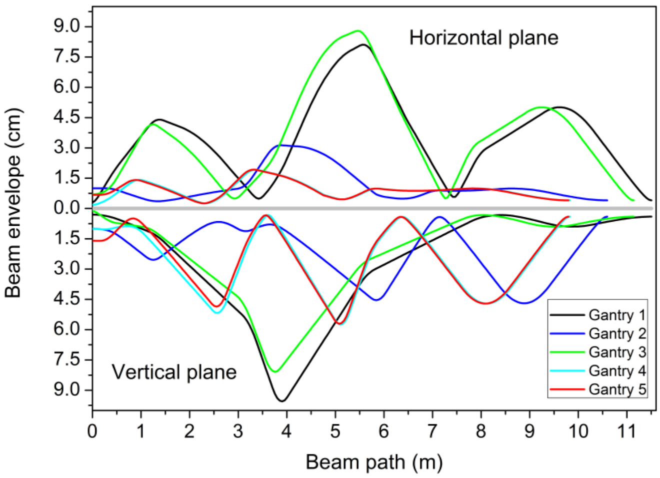

Fig. 5.4 Horizontal (upper) and vertical (lower) beam envelopes inside all proton gantry versions in terms of FWHM.

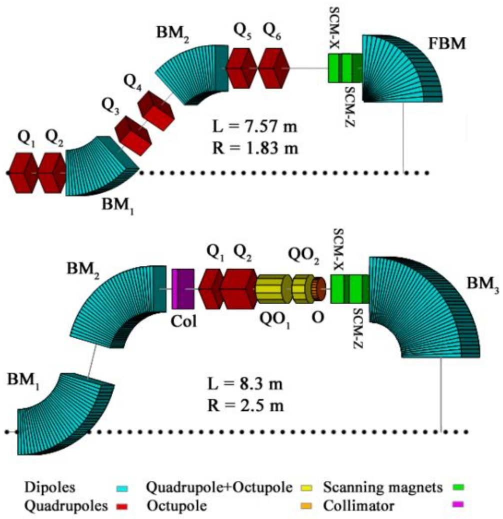

Fig. 5.5 Schematic 3D sketches of my proton gantry using the hybrid beam transport system with the superconducting final bending magnet designed by Caspi et al. [30, 31] (upper), and the LBNL/PSI superconducting proton gantry [59] (lower). BM_i – bending magnets, Q_i – quadrupole magnets, SCM-X – horizontal scanning magnet, SCM-Z – vertical scanning magnet, FBM – final bending magnet, QO_i – quadrupole+octupole combined function magnets, O – octupole magnet, Col - collimator, L – gantry length, R – gantry radius. The transverse physical dimensions of individual elements are only approximately to scale.

Upstream and parallel scanning in both directions has been foreseen in the design of the superconducting final bending magnet by magnet designers. Superconducting combined function magnet has a circular bore with a clear diameter of 130 mm. I have verified that only a rectangular 11.0 × 3.2 cm^2 scanning field is feasible taking into account this circular aperture and 4 mm (FWHM) beam spot-size at the isocenter. I have tried to increase the scanning field by varying the beam spot-size at the isocenter. The results are summarized in Table 5.2. The most significant increase of the scanning field corresponds to 6 mm (FWHM) beam spot-size at the isocenter. The effective scanning area was enlarged to 11.0 × 7.0 cm^2. In order to ensure some clearance at the vacuum chamber wall and suppress the beam losses inside the final bending magnet, I have reduced this scanning field to the 9.5 × 7.0 cm^2 rectangle (see Fig. 5.6). This scanning field is still not quite enough for standard proton therapy, but it represents the best results that could be achieved for such large beam emittances and small magnet clear bore. The study of the scanning field area dependence on the beam spot-size at the isocenter has showed the ion-optical flexibility of my gantry design. Different beam spot-sizes at the gantry isocenter were achieved by minor re-tuning of the quadrupole magnets.

Table 5.2 Selected beam spot-sizes at the gantry isocenter with corresponding effective scanning field area values.

Beam size (FWHM)	RMS Beam size	Effective Scanning field area
4 mm	1.7 mm	11.0 × 3.2 cm^2 ≈ 35 cm^2
5 mm	2.1 mm	11.0 × 6.0 cm^2 ≈ 66 cm^2
6 mm	2.5 mm	11.0 × 7.0 cm^2 ≈ 77 cm^2
7 mm	3.0 mm	11.0 × 7.2 cm^2 ≈ 79 cm^2
8 mm	3.4 mm	10.6 × 8.0 cm^2 ≈ 85 cm^2
9 mm	3.8 mm	10.8 × 8.0 cm^2 ≈ 87 cm^2
10 mm	4.2 mm	10.8 × 8.2 cm^2 ≈ 89 cm^2

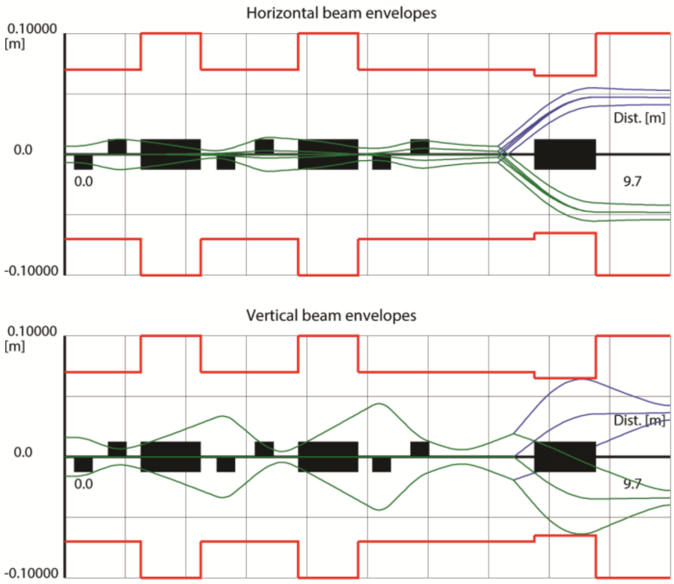

Fig. 5.6 Beam scanning for 9.5 × 7.0 cm^2 rectangular field with 6 mm FWHM beam spot-size at the isocenter and maximum deflections individually in both transverse planes (FWHM beam envelopes are shown). F_x = 0.590 m and F_z = 0.334 m are the focal points of the final bending magnet in the horizontal and vertical plane, respectively. The black boxes indicate the gantry magnets and the red line defines the physical aperture of the gantry beam line.

The final proton gantry version profits from the most advanced technique for matching the non-symmetric beams – the rotator. The most compact design of the rotator has been achieved for the general rotator lattice. A straight quadrupole rotator lattice fulfils the condition (22) keeping the horizontal and vertical phase advances shifted by π with respect to each other. It corresponds very well to the final proton gantry design with identical input beta-functions. The equal input beta functions of the rotator were sequentially varied from 0.5 m to 5.0 m with 0.5 m step. The best result was reached for 2.0 m input beta functions of the rotator. Fig. 5.7 shows the corresponding beta functions of the rotator. The horizontal and vertical phase advance is 3.9070 and 0.7654, respectively. The transfer matrix of this rotator, $\mathbf{M}_{\mathbf{ROT,3}}$, is:

$$\mathbf{M}_{\mathbf{ROT,3}} = \begin{pmatrix} -0.721 & -1.386\,m & 0 & 0 \\ 0.346\,m^{-1} & -0.721 & 0 & 0 \\ 0 & 0 & 0.721 & 1.386\,m \\ 0 & 0 & -0.346\,m^{-1} & 0.721 \end{pmatrix}. \tag{23}$$

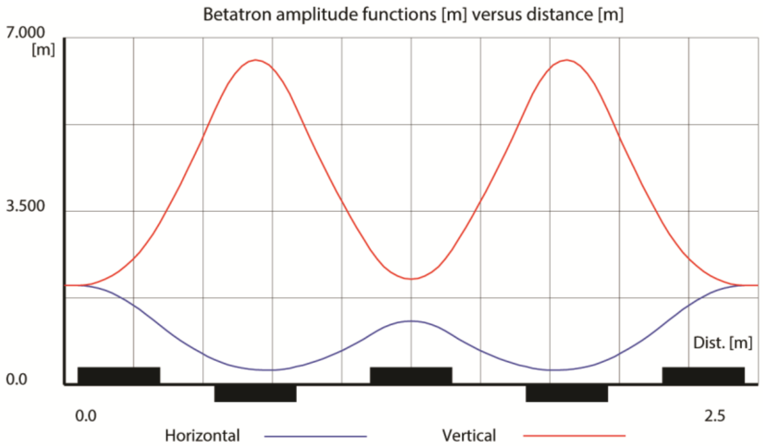

Fig. 5.7 Beta functions of the rotator with the general rotator transfer matrix for the proton gantry. Quadrupoles are indicated by the black boxes: upper orientation – a horizontally focusing quadrupole, bottom orientation – a vertically focusing quadrupole.

The ion-optical and physical rotator settings are listed in Table 5.3. It consists of five quadrupoles grouped into three families Q1=Q5, Q2=Q4 and Q3. The final length of the rotator is 2.54 m, which represents the shortest rotator lattice designed for the proton gantry in my work. Functionality of the rotator is verified and illustrated in Fig. 5.8. The left panels show the beam spots at the gantry isocenter without using the rotator. One can evidently see the angular dependence of the beam spot. The right panels show the beam spots with using the rotator installed upstream of the gantry. As it can be seen, the angular dependence of the beam spot is eliminated. The complete layout of the gantry with the rotator is shown in Fig. 5.9.

Table 5.3 The rotator settings corresponding to the rotator with general rotator transfer matrix for the proton gantry- $\boldsymbol{M}_{ROT,3}$. The following abbreviations are used: d = drift length, L_{eff} = effective length of a quadrupole, A_p = quadrupole half-aperture, B = magnetic flux density on the quadrupole pole tip ("+" for vertical focusing). The WinAGILE sign convention for magnetic field components is applied.

Element	Physical and magnetic parameters		
Drift	d = 0.05 m		
Quadrupole 1	L_{eff} = 0.30 m	A_p = 4.0 cm	B = -0.497 T
Drift	d = 0.20 m		
Quadrupole 2	L_{eff} = 0.30 m	A_p = 4.0 cm	B = +0.640 T
Drift	d = 0.27 m		
Quadrupole 3	L_{eff} = 0.30 m	A_p = 4.0 cm	B = -0.998 T
Drift	d = 0.27 m		
Quadrupole 4	L_{eff} = 0.30 m	A_p = 4.0 cm	B = +0.640 T
Drift	d = 0.20m		
Quadrupole 5	L_{eff} = 0.30 m	A_p = 4.0 cm	B = -0.497 T
Drift	d = 0.05 m		

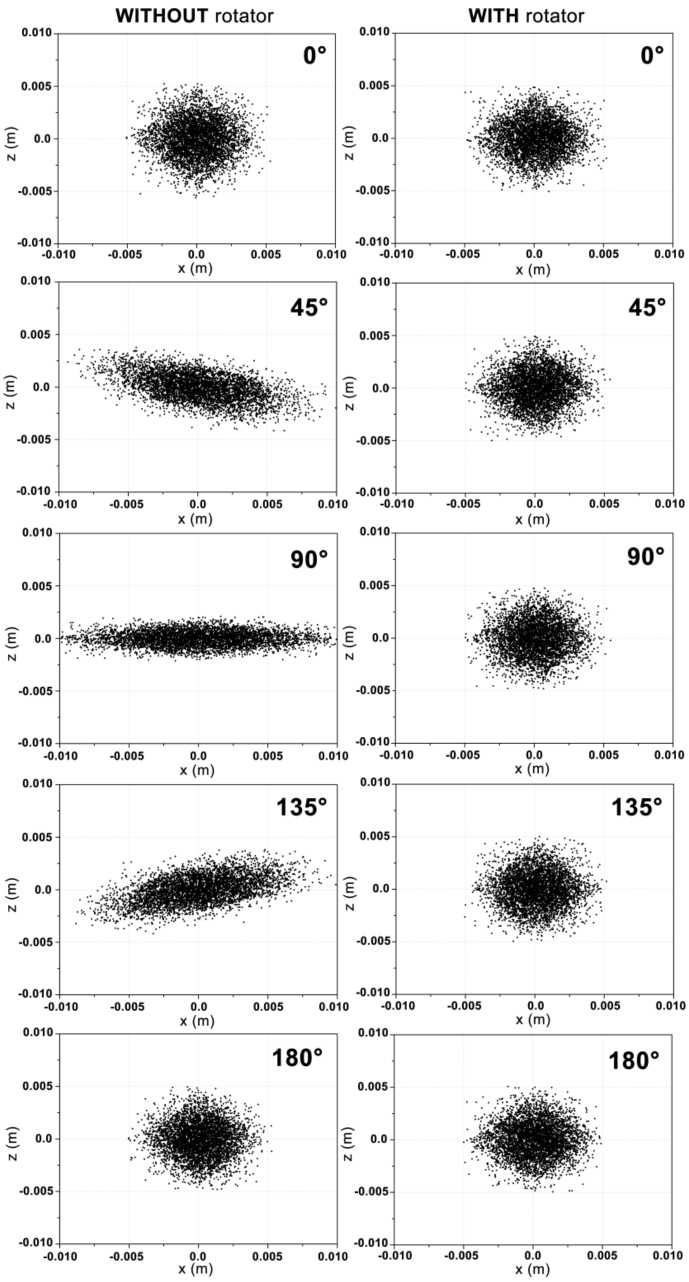

Fig. 5.8 Beam spots at the gantry isocenter for five angles of the gantry rotation, namely 0°, 45°, 90°, 135° and 180°. Left panels – gantry rotation without using rotator. Right panels – gantry rotation with using rotator installed upstream of the gantry.

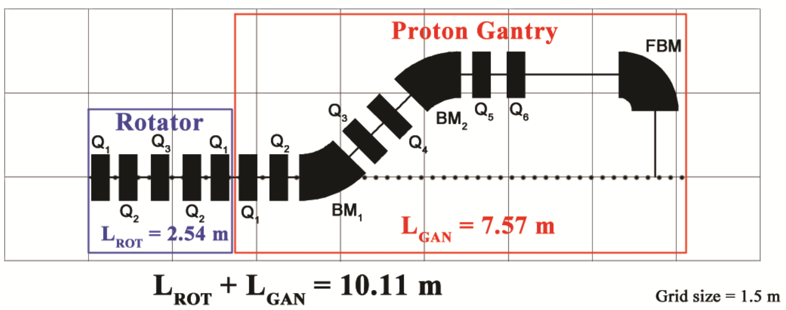

Fig. 5.9 Complete layout of the proton gantry with the final rotator design. L_{GAN} – gantry length, L_{ROT} – rotator length, BM_i – bending magnets (dipoles), FBM – final bending magnet, Q_i – quadrupole magnets.

5.2 Carbon-Ion Gantry Design

The most important specifications that were used for the design of my carbon-ion gantry are listed below:

1. Isocentric configuration;
2. Overall gantry size and weight as small as possible;
3. Minimum drift space from the gantry exit to the isocenter 1.2 m;
4. Double-achromatic beam optics;
5. Beam waists at the isocenter;
6. Reference output beam size at the isocenter 4 mm (FWHM);
7. Beam rigidity 6.345 Tm (limited by the SC-magnet design). This rigidity corresponds to 400 MeV/u C^{6+} with penetration range in water of 28 cm;
8. Upstream and parallel scanning in both directions (the parallel scanning mode has been again foreseen in the design of the superconducting final bending magnet [29, 32]).

The scheme of the conceptual gantry layout is visualized in Fig. 5.10. The major goal was to obtain a minimal gantry size.

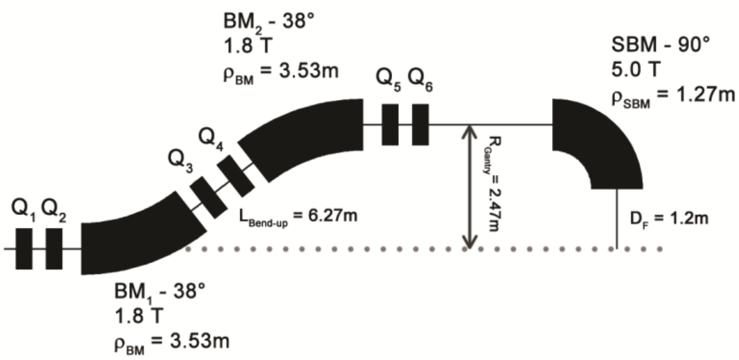

Fig. 5.10 Scheme of the initial carbon-ion gantry setup.

I have chosen the 5 T toroidal superconducting 90° magnet described in Refs. [29, 32, 33] as the final bending magnet for my carbon-ion gantry. It has been designed specifically for application in heavy-ion gantries. The coil of this magnet is curved 90° at the radius of 1269 mm. It has 250 mm clear bore. The gantry optics was designed for non-symmetric carbon-ion beam with the nominal kinetic energy of 400 MeV/u. The beam emittances of $\varepsilon_x = 1\pi$ mm.mrad and $\varepsilon_z = 5\pi$ mm.mrad were assumed in the transverse planes [60].

The most compact carbon-ion gantry version has been found for the equal input beta-functions with the bigger beam emittance in the vertical gantry plane. The input beta-functions varied from 1 m to 15 m with 0.5 m step. The best result was achieved for 13.5 m input beta function. The gantry layout is shown in Fig. 5.11. The length and radius of this gantry is 11.31 m and 2.47 m, respectively. The ion-optical settings are listed in Table 5.4.

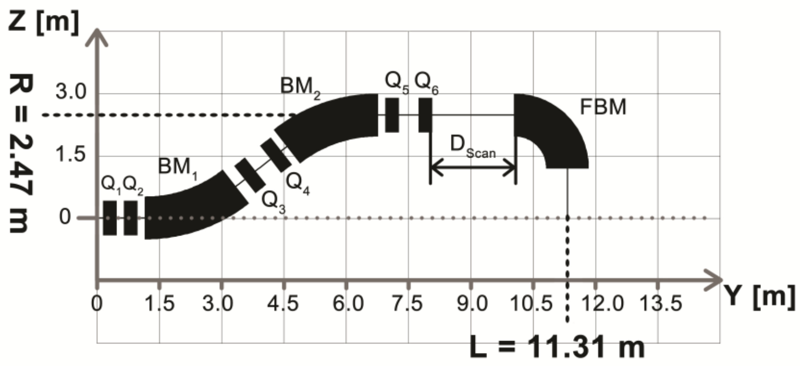

Fig. 5.11 Layout of the carbon-ion gantry with equal input beta functions of 13.5 m (the vertical plane of the gantry receives the bigger beam emittance). R – gantry radius, L – gantry length, BM_i - bending magnets (dipoles), FBM – final bending magnet, Q_i – quadrupole magnets, D_{Scan} – drift for a scanning system.

Table 5.4 The gantry settings corresponding to the layout in Fig. 5.11. The following abbreviations are used: d = drift length, L_{eff} = effective length of a quadrupole, A_p = quadrupole half-aperture, B = magnetic flux density on the quadrupole pole tip ("+" for vertical focusing), B_{BEND} = magnetic flux density of the dipole magnet, B_{QUAD} = 1st order magnetic field gradient (quadrupole term), B_{SEXT} = 2nd order magnetic field gradient (sextupole term). The WinAGILE sign convention for magnetic field components is applied.

Element	**Physical and magnetic parameters**		
Drift	d = 0.15 m		
Quadrupole 1	L_{eff} = 0.30 m	A_p = 4.25 cm	B = +0.628 T
Drift	d = 0.20 m		
Quadrupole 2	L_{eff} = 0.30 m	A_p = 4.25 cm	B = -0.831 T
Drift	d = 0.20 m		
38° Bending magnet 1	B_{BEND} = 1.8 T		
Drift	d = 0.30 m		
Quadrupole 3	L_{eff} = 0.30 m	A_p = 4.25 cm	B = +0.554 T
Drift	d = 0.49 m		
Quadrupole 4	L_{eff} = 0.30 m	A_p = 4.25 cm	B = -0.990 T
Drift	d = 0.20m		
38° Bending magnet 2	B_{BEND} = 1.8 T		
Drift	d = 0.20 m		
Quadrupole 5	L_{eff} = 0.30 m	A_p = 4.25 cm	B = +0.745 T
Drift	d = 0.50 m		
Quadrupole 6	Leff = 0.30 m	A_p = 4.25 cm	B = -0.986 T
Drift for the scanning system	d = 2.00 m		
90° final bending magnet	B_{BEND} = 5.0 T	B_{QUAD} = +2.26 T/m	B_{SEXT} = -1.30 T/m^2
Drift to the patient	d = 1.2 m		

The lattice functions are plotted in Fig. 5.12 (left panel). The right panel shows the beam envelopes. The beam envelopes occupy the smallest aperture from all investigated cases. The reduction of the beam-line aperture reaches in the final gantry version a factor of about 2 in comparison with other gantry versions, see Fig. 5.13. Smaller aperture means also lighter magnets, hence also less massive gantry supporting structure.

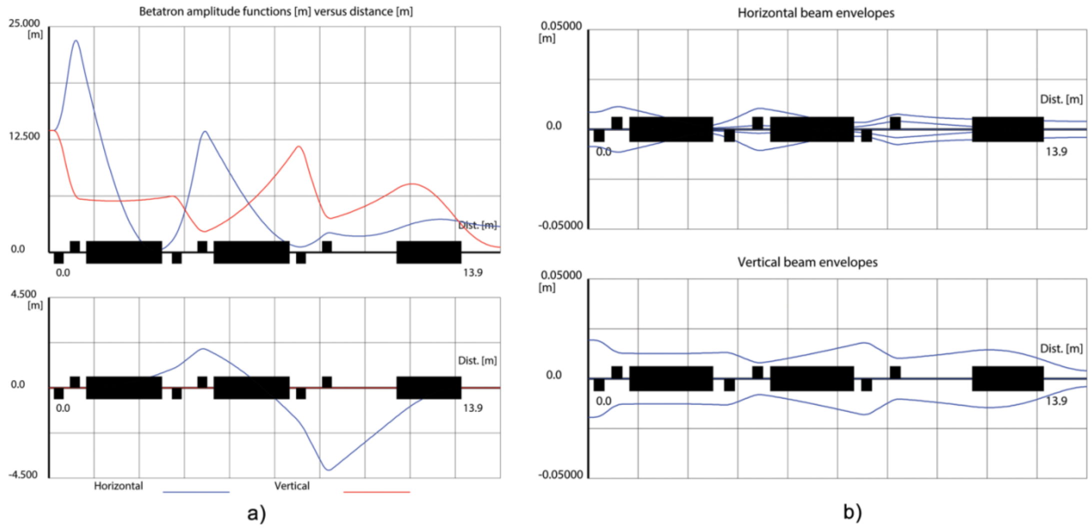

Fig. 5.12 a) Beta functions (upper) and dispersion functions (lower) in the horizontal (blue) and vertical (red) plane. b) Horizontal (upper) and vertical (lower) beam envelopes in terms of FWHM. The black boxes indicate the gantry magnets.

The volume occupied by the gantry is 195 m^3. The superconducting rotating gantry designed at GSI Darmstadt in 1997 [61] was 16.75 m long with 2.5 m radius. It occupied the volume of 258 m^3. The length and radius of the NIRS/HIMAC superconducting gantry designed by Iwata et al. [35–37] is 13 m and 5.5 m, respectively, which corresponds to the volume of 1235 m^3. Moreover, this gantry is not capable of transporting the non-symmetric beams. Fig. 5.14 shows 3D sketches of my carbon-ion gantry using the hybrid beam transport system with the superconducting final bending magnet, and the NIRS/HIMAC gantry [35]. At the moment, no data concerning the gantries' weight are available. The weight of the NIRS/HIMAC gantry is not quoted in the literature and my gantry design does not include a design of the mechanical supporting structure. Nevertheless, the gantry dimensions are close to the existing proton gantries and the resistive part of its beam transport system is composed from magnets similar to the magnets used at proton gantries. That is why one can expect also the gantry weight to be similar to the weight of the existing proton gantries of the same concept (barrel-like geometry, upstream scanning).

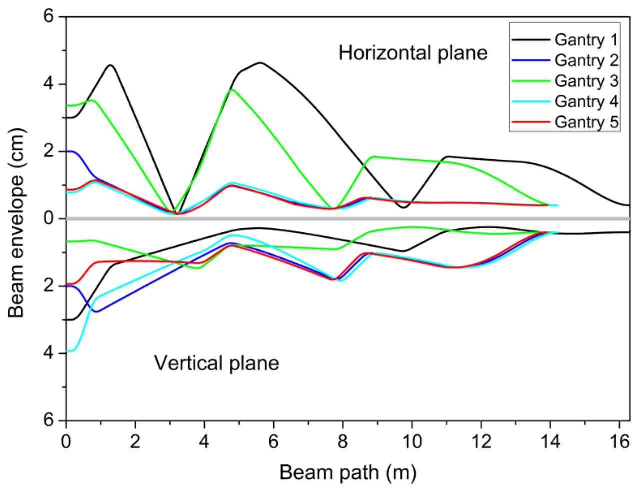

Fig. 5.13 Horizontal (upper) and vertical (lower) beam envelopes inside all carbon-ion gantry versions in terms of FWHM.

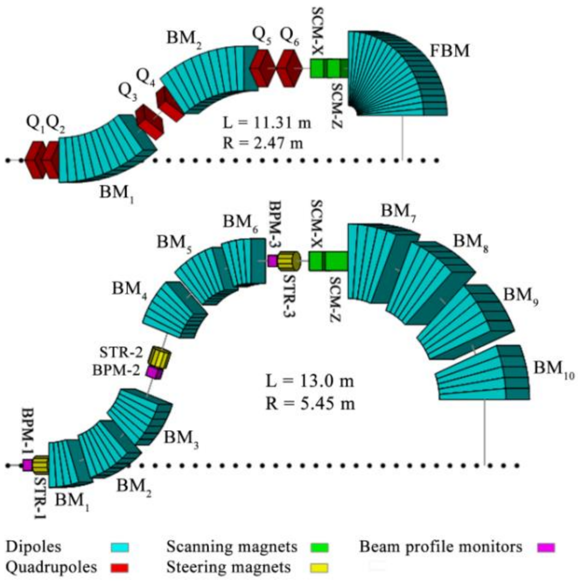

Fig. 5.14 Schematic 3D sketches of my gantry using the hybrid beam transport system with the superconducting final bending magnet designed by Caspi et al. [29, 32, 33] (upper), and the NIRS/HIMAC gantry [35] (lower). BM_i – bending magnets, Q_i – quadrupole magnets, SCM-X – horizontal scanning magnet, SCM-Z – vertical scanning magnet, FBM – final bending magnet, BPM-i – beam profile monitors, STR-i – steering magnets, L – gantry length, R – gantry radius. The transverse physical dimensions of individual elements are only approximately to scale.

The gantry provides upstream 2D parallel scanning in both directions. It was verified that circular scanning field with the diameter of 21.21 cm as the diagonal of the 15 × 15 cm^2 square is feasible taking into account the circular aperture of the final superconducting bending magnet and the 4 mm (FWHM) beam spot-size at the isocenter, see Fig. 5.15. It covers 353 cm^2 area of the circular magnet bore cross-section which complies with the conclusion of a European survey for the minimum required scanning field [29, 62]. Moreover, this specification is well within what has already been achieved for example in the NIRS/HIMAC gantry design [35].

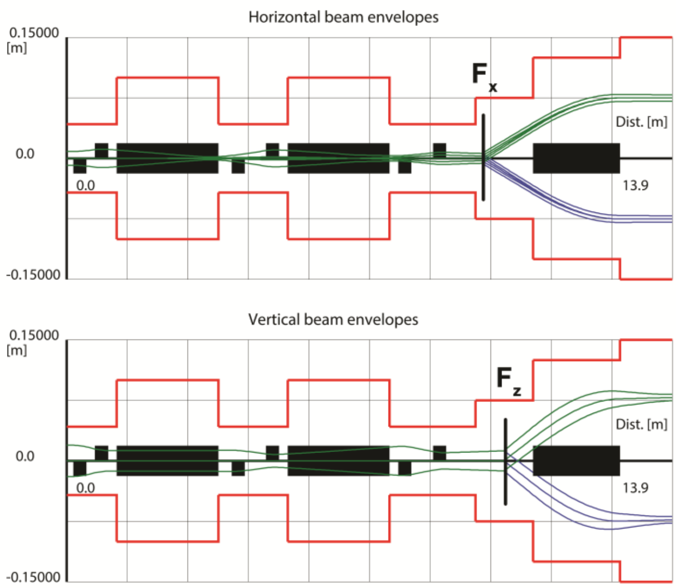

Fig. 5.15 Beam scanning for the 15 × 15 cm^2 squared field with maximum deflections individually in both transverse planes (FWHM beam envelopes are shown). F_x = 1.177 m and F_z = 0.671 m are the focal points of the final bending magnet in the horizontal and vertical plane, respectively. The black boxes indicate the gantry magnets and the red line defines the physical aperture of the gantry beam line.

I also investigated a possibility of prolongation of the last drift to gain more space around the patient and to avoid the magnet stray-fields. I have found out that the presented carbon-ion gantry design exhibits high level of ion-optical flexibility thanks to the hybrid concept and the rotator. The rotator relaxes the ion-optical constraints imposed on the gantry and the resistive quadrupoles can be easily adjusted to different excitation and used as variables for fitting of different ion-optical constraints. This is an advantage not only during gantry operation, but even more during the design phase. A gantry version with a longer drift from the final bending magnet to the patient (1.9 m) was designed, too.

As far as the rotator design is concerned, the most compact design of the rotator has been achieved for the general rotator lattice as in the case of the proton gantry. The equal input beta functions were sequentially varied from 5.0 m to 15.0 m in 0.5 m steps. The best result was reached for 13.5 m input beta functions. Fig. 5.16 shows the resulting rotator beta functions. Horizontal and vertical phase advance is 3.9070 and 0.7654, respectively. The transfer matrix of this rotator, $\mathbf{M}_{\mathbf{ROT,3}}$, is:

$$\mathbf{M}_{\mathbf{ROT,3}} = \begin{pmatrix} 0.959 & 3.820\,m & 0 & 0 \\ -0.021\,m^{-1} & 0.959 & 0 & 0 \\ 0 & 0 & -0.959 & -3.820\,m \\ 0 & 0 & 0.021\,m^{-1} & -0.959 \end{pmatrix}. \tag{24}$$

The ion-optical and physical rotator settings are listed in Table 5.5. It consists of seven quadrupoles grouped into three families Q1=Q7, Q2=Q6, Q3=Q5 and Q4. The final length of the rotator is 4.1 m, which represents the shortest rotator lattice designed for carbon-ion gantry in my work. Functionality of the rotator is verified and illustrated in Fig. 5.17. As it can be seen, the angular dependence of the beam spot at the gantry isocenter is eliminated with the rotator installed upstream of the gantry. The complete layout of the final carbon-ion gantry with the rotator is shown in Fig. 5.18.

Table 5.5 The rotator settings corresponding to the rotator with general rotator transfer matrix for carbon-ion gantry - $\boldsymbol{M}_{ROT,3}$. The following abbreviations are used: d = drift length, L_{eff} = effective length of a quadrupole, A_p = quadrupole half-aperture, B = magnetic flux density on the quadrupole pole tip ("+" for vertical focusing). The WinAGILE sign convention for magnetic field components is applied.

Element	**Physical and magnetic parameters**		
Drift	d = 0.05 m		
Quadrupole 1	L_{eff} = 0.40 m	A_p = 4.0 cm	B =+0.671 T
Drift	d = 0.20 m		
Quadrupole 2	L_{eff} = 0.40 m	A_p = 4.0 cm	B = -0.979 T
Drift	d = 0.20 m		
Quadrupole 3	L_{eff} = 0.40 m	A_p = 4.0 cm	B = +0.424 T
Drift	d = 0.20 m		
Quadrupole 4	L_{eff} = 0.40 m	A_p = 4.0 cm	B = +0.952 T
Drift	d = 0.20 m		
Quadrupole 5	L_{eff} = 0.40 m	A_p = 4.0 cm	B = +0.424 T
Drift	d = 0.20 m		
Quadrupole 6	L_{eff} = 0.40 m	A_p = 4.0 cm	B = -0.979 T
Drift	d = 0.20 m		
Quadrupole 7	L_{eff} = 0.40 m	A_p = 4.0 cm	B = +0.671 T
Drift	d = 0.05 m		

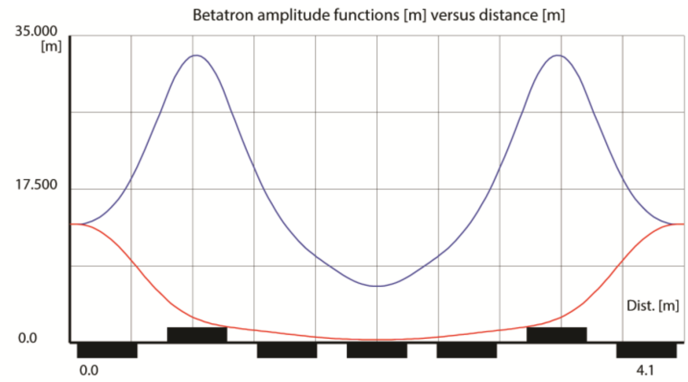

Fig. 5.16 Beta functions of the rotator with the general rotator transfer matrix for the carbon-ion gantry. Quadrupoles are indicated by the black boxes: upper orientation – a horizontally focusing quadrupole, bottom orientation – a vertically focusing quadrupole.

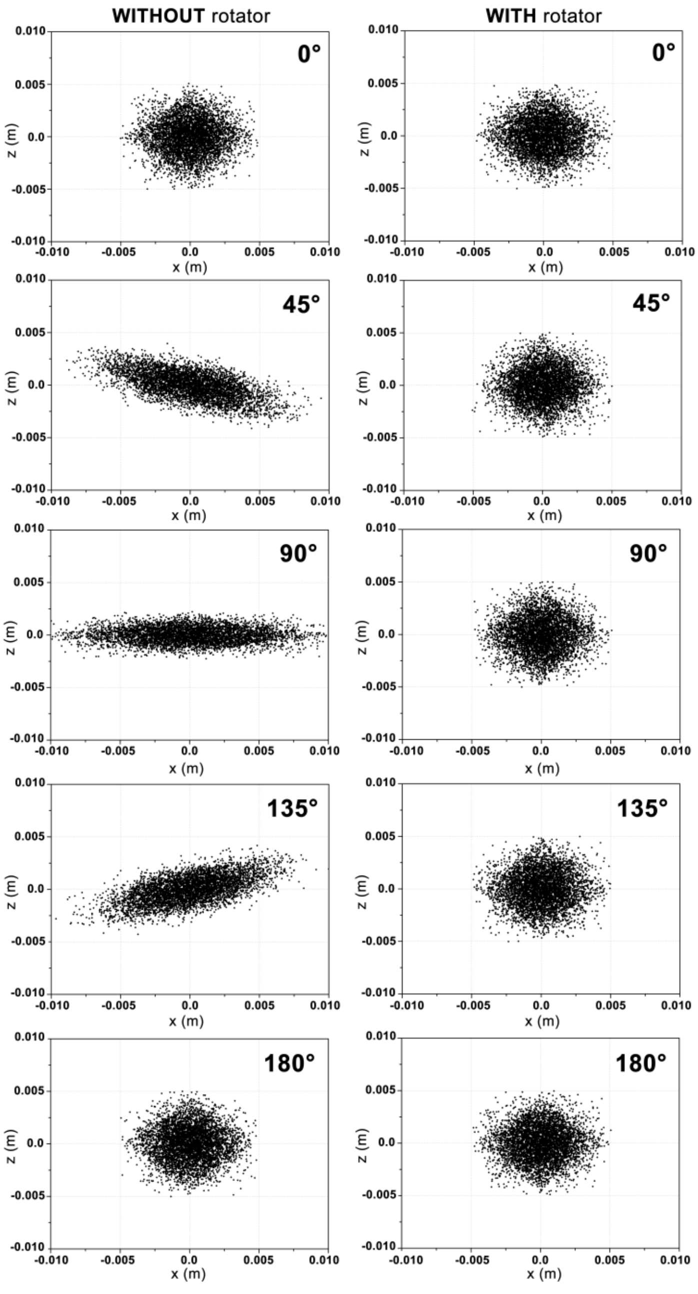

Fig. 5.17 Beam spots at the gantry isocenter for five angles of the gantry rotation, namely 0°, 45°, 90°, 135° and 180°. Left panels – gantry rotation without using the rotator. Right panels – gantry rotation with using the rotator installed upstream of the gantry.

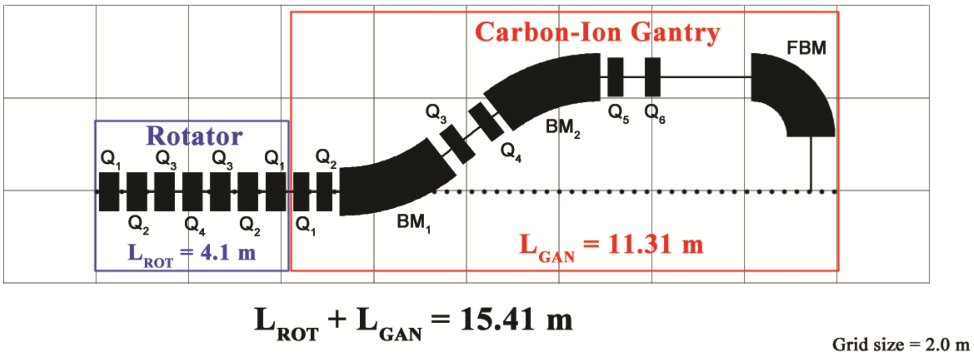

Fig. 5.18 Complete layout of the carbon-ion gantry with the final rotator design. L_{GAN} – gantry length, L_{ROT} – rotator length, BM_i – bending magnets (dipoles), FBM – final bending magnet, Q_i – quadrupole magnets.

CONCLUSION

In this dissertation thesis, an ion-optical design of a compact isocentric rotating gantry for proton as well as heavy-ion therapy has been performed. A hybrid beam transport system has been introduced. The hybrid beam transport system uses conventional, i.e. resistive magnets combined with the superconducting final bending magnet. The parameters of the superconducting bending magnets are based on real prototypes. The hybrid beam transport systems have been matched to their ion optical properties of the selected superconducting magnets. Final gantries are capable of transporting non-symmetric beams and 2D parallel pencil-beam scanning. Such hybrid beam transport systems have been designed for the first time. Several gantry designs were elaborated and the most compact versions have been selected. In order to design a compact gantry, the number of quadrupoles was kept down to theoretical minimum. Six ion-optical constraints were fitted with the aid of six quadrupoles as fitting variables.

The gantry designs profit from the most advanced technique for matching the non-symmetric beams to rotating ion-optical systems – the rotator. This allows selecting the “working mode” of the gantry. I have found out that smaller beam envelopes inside the gantries were obtained, when the vertical gantry plane received the bigger beam emittance. The thesis also revealed the importance of the optimization of the input beam parameters. The case with identical input beta functions showed considerably smaller beam envelopes compared to equal beam-size or equal beam-divergence cases (roughly by a factor of 2). This case (i.e. equal input beta functions) is also well suited for the design of the rotators that is also included in the thesis.

ZÁVER

V dizertačnej práci je prezentovaný ióno-optický návrh kompaktnej izocentrickej rotačnej gantry pre protónovú a iónovú terapiu. Základom práce je hybridný koncept rotačnej gantry, ktorý predstavuje kombináciu klasických (“teplých”) elektromagnetov s koncovým supravodivým magnetom. Parametre tohto supravodivého magnetu sú založené na existujúcom prototype, pričom ióno-optický systém gantry je prispôsobený k ióno-optickým vlastnostiam tohto magnetu. Konečný návrh oboch verzií gantry umožňuje transport nesymetrických iónových zväzkov a 2D paralelné skenovanie. Takýto hybridný koncept bol navrhnutý po prvý krát. Na základe viacerých verzií bol vybratý najkompaktnejší návrh pre protónovú, ako aj iónovú gantry. Pri návrhu gantry bol použitý minimálny počet kvadrupólov, aby sa dosiahla čo najkompaktnejšia konfigurácia gantry. Šesť ióno-optických parametrov bolo regulovaných pomocou šiestich kvadrupólov, ktoré boli pri návrhu používané ako premenné.

Návrhy oboch verzií gantry profitujú z najmodernejšej metódy transportu nesymetrických iónových zväzkov cez rotačné ióno-optické systémy, ktorá sa zakladá na tzv. rotátore. Toto riešenie umožňuje zvoliť “pracovný režim” gantry. Zistil som, že menšie obálky zväzku sa dosahujú v prípade, keď väčšia emitancia zväzku je transportovaná vertikálnou rovinou gantry. Moja práca tiež preukázala, aká dôležitá je optimalizácia vstupných parametrov zväzku. Pri rovnakých vstupných beta funkciách v oboch priečnych rovinách gantry boli obálky zväzku podstatne menšie v porovnaní s prípadmi rovnakého vstupného rozmeru zväzku alebo rovnakej vstupnej divergencie zväzku (približne 2-krát). Rovnaké vstupné beta funkcie sú navyše vhodné aj pre návrh rotátorov, ktorý je tiež súčasťou dizertačnej práce.

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