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ScienceDirect

Physics Procedia 90 (2017) 223 – 228

Physics Procedia

Conference on the Application of Accelerators in Research and Industry, CAARI 2016,
30 October – 4 November 2016, Ft. Worth, TX, USA

New Beam Scanning Device for Active Beam Delivery System (BDS) in Proton Therapy

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Abstract

A new Beam Delivery System (BDS) has been studied in the framework of a new proton therapy project, called AMIDERHA. It is characterized by an active scanning system for target irradiation with a pencil beam. The project is based on the use of a Linac with variable final energy and the Robotized Patient Positioning System instead of the traditional gantry. As a consequence, in the active BDS of AMIDERHA a pencil beam scanning system with a relatively long Source to Axis Distance (SAD) can be used. In this contribution, the idea of using a unique new device capable of both horizontal and vertical beam scansion for the AMIDERHA active BDS will be presented and discussed. Furthermore, a preliminary design of that device will be shown, together with the results of simulations.

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Keywords: Beam scanning; Beam delivery dose

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1. Introduction

Recently, a new hadrotherapy center, named AMIDERHA, has been partially funded for operating in the South-Italy (Ref. 2013). The AMIDERHA project considers new solutions for cancer treatments: the accelerator used is a LINAC

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Peer-review under responsibility of the Scientific Committee of the Conference on the Application of Accelerators in Research and Industry
doi:10.1016/j.phpro.2017.09.062

that can deliver a proton beam with variable energy between 70 and 150 MeV. In this project, the gantry has been replaced by the use of a movable patient positioning system.

The AMIDERHA Beam Delivery System (BDS), is characterized by a dedicated transport channel capable of delivering a beam of different energies from the LINAC, a unique magnetic system device for scanning the beam in both horizontal and vertical planes and a Robotized Patient Positioning System (RPPS). The transport channel and the scanning system allow the protons to reach the tumor target and release the required radiation dose on an extended volume. The design of the channel allows the beam to hold its pencil shape, i.e. a diameter smaller than about 7 mm (Amiderha, 2013).

Although the beam is fixed, the RPPS allows, in principle, a complete tumor treatment in any part of the body patient thanks to suitable movements of the patient bed. The system is divided in three modules perfectly interacting with each other, which allows to scan the patient by Computed Tomography (CT) and to guide the technician during the treatment thanks a Stealth Navigation Module (Amiderha, 2013). At NIRS – HIMAC in Japan, a similar project, still under development, will also provide a treatment based on patient positioning, giving away completely the gantry (as reported by T. Furukawa et al., 2009).

The BDS beam transport channel consists of focusing elements, such as quadrupoles, bending magnets to drive the beam at the treatment room, the beam magnetic scanning system and the RPPS apparatus. Obviously instrumentation for monitoring the beam delivered on the target volume has been foreseen in order to check the uniformity of the released dose (less than 2 ÷ 3%).

Since the AMIDERHA Linac could deliver a proton beam of different energies (from 70 up to 150 MeV) the beam transport channel also has been designed to preserve good beam qualities up to the magnetic scanning system for different beam energies. Such goal could be obtained by slightly changing the bending field and the strength of a few quadrupoles. The beam transport design simulation for proton beam with energy of 150 MeV has been carried out by means of the TRACE 3D code (K. R. Crandall, 1990). It has allowed us to find the right quadrupole gradient values and the proper drift lengths to be used in the BDS beam line. A detailed beam simulation that includes particle distribution along the transport channel has been carried out by using the PARMILA code (H. Takeda, 2005). In that code the input values for the beam simulations in all phase spaces were the same of the TRACE 3D input. For particles with different energies the beam is no more matched, so new beam matching conditions should be searched for a different beam energy. Since the quadrupole lengths and “drifts” could not be changed once the beam line for treatment is built, only the quadrupole gradients have to be changed to reach the new beam matching conditions. The beam scanning magnetic system capable of deflecting the pencil beam which delivers the dose will be placed just before the last drifts. Usually, the magnetic system consists of two bending magnets, one each for the beam scanning in the horizontal and vertical planes. For the BDS of the AMIDERHA project a unique magnetic device capable of the beam scanning in both horizontal and vertical plane has been proposed. In this paper the conceptual idea of the system will be presented and discussed, along with a preliminary design.

2. The scanning magnet design

Currently, Beam Delivery Systems with pencil beam scanning offer the best flexibility for shaping the dose distribution. The magnetic scanning system has the task of deflecting the beam in both horizontal and vertical plane in order to drive it on the different parts (voxel) in which the tumor mass volume is formally divided.

Up to now, two kinds of beam scanning techniques have been proposed and used: the ‘raster scanning’ (by T. Haberer et al., 1993) and the ‘spot by spot scanning’ (by F. Pedroni et al., 1995). Both techniques use two dipole magnets, one for the horizontal plane and the other one for the vertical plane deflection. In the ‘spot by spot’ case the electromagnet circulating currents used to generate the proper magnetic field are controlled electronically in such a way that the proton beam spot could reach in succession the ‘voxels’ which compose the tumor volume. In the ‘raster’ technique the electromagnet currents are controlled in such a way that a horizontal scansion is applied first for the whole extension of the tumor. Subsequently, the proton beam is lowered vertically and a new horizontal scansion is performed, to cover the whole transverse surface of the tumor. The scansion along the depth of the tumor is obtained by the proper variation of the beam energy.

Both scanning systems need the design of two dipole magnets for the deflection in the horizontal and vertical plane. The standard magnetic dipoles used for the beam transport of charged particles usually are designed to bent a beam of certain energy for a fixed angle. The dipole magnet of a scanning system, instead, should deflect the charged beam to variable angles also with the possibility of changing their sign. Such a bending feature does not allow to use standard dipole magnets but proper magnet devices have to be designed. Furthermore, the transport channel design must fulfill the constraints that the pencil beam quality is preserved up to the beam scanning system that distributes the required dose on the tumor volume. The pencil type proton beam has a very low emittance (~1 πmm mr) and a circular spot with a diameter lower than about 7 mm.

Three standard families of dipole magnets are typically used in particle accelerators and transfer lines; the so-called: C-magnet, the H-magnet and the O- (or window-frame) magnet (the capital letters refer to their iron yoke shape). They all have their advantages and drawbacks. The choice for one or the other option is led by the constraints and requirements such as the function of the magnet, the available space, and the field quality. The H-type magnet is used as standard in many accelerators and beam transfer lines. Access to the coils and beam pipes is poor, but they provide a good mechanical stability and symmetric field quality. Furthermore, the iron weight of the yokes is reduced with respect to C-magnets. The O-magnet has similar characteristics to the H-magnet in terms of good symmetry, weight, and mechanical stability, with the difference that the window-frame design provides a very homogenous field quality. It is worth noticing that in the case of the O-magnet the coils can also be installed around the horizontal leg of the magnetic circuit adding a vertical bending function (see fig. 1). Such combined horizontal/vertical magnets are often used as steering magnets due to their compact design, but their excitation efficiency is low. In general, the beam scanning systems for active dose delivery use very low deflecting angles, as reported for example in T. Furukawa, 2009, where the scanning magnets prototypes at HIMAC facility (Chiba, Japan) are presented. The maximum deflecting angle considered in that case is 18 mrad (≈ 1°) in the horizontal plane and 21 mrad (≈ 1.2°) in the vertical plane.

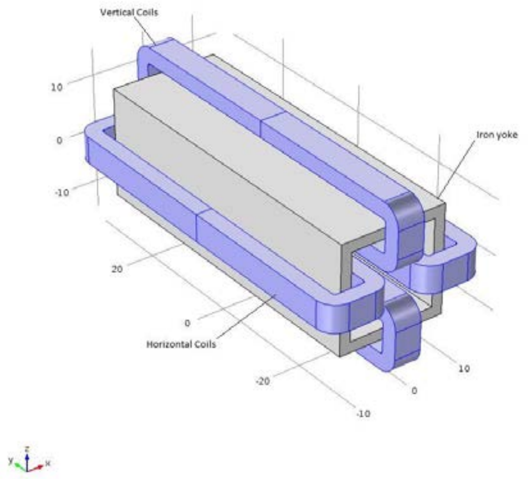


Figure 1. Dipole O-magnet type with horizontal and vertical coils to deflect the proton beam in both the horizontal and vertical direction.

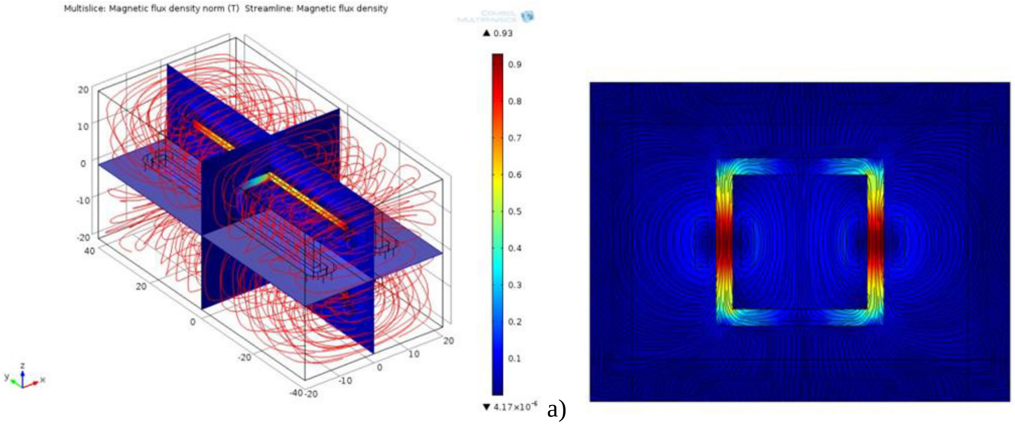
These angles allow a scanning extension of about 30 cm in the horizontal and vertical directions at a distance of 8.4 and 7.6 m, respectively (from the iso-center). In fact, the use of a beam scanning for delivering a dose on the patient implies that the pencil beam enters in the patient body with a certain angle with respect to the central axis of the tumor volume. If the beam is scanned with large angles a relative high skin dose can be absorbed with respect to the tumor dose at depth. For that reason, the beam scanning magnets are usually placed at a relatively long distance from the patient. For a tumor depth of 30 cm, the acceptable Source to Axis Distance (SAD), should be higher than 2 m (D. Robin, 2001) to keep the dose increase on the skin area, relative to the parallel beam case, lower than 40% (as an example, for SAD longer than 6 m the skin area dose increase is lower than 5%).

The low values of the deflecting angles used in the beam scanning systems suggested us the possibility of using a unique O- magnet type with horizontal and vertical coils capable, as mentioned above, to steer the beam both in vertical and horizontal direction.

The constraints given by the AMIDERHA project were a proton beam energy of 150 MeV (for pediatric proton therapy), a SAD of 6 ÷ 7 m, and a squared scanning surface with a side of 40 ÷ 50 cm, corresponding to a deflecting angle lower than 2° (35 mr).

The magnetic rigidity R can be expressed (T. Zickler, 2010) as $B\rho[Tm] = 3.3356\ x\ p\ [GeV/c]$. For a proton beam energy of 150 MeV, p = 0.53 GeV/c, R=1.7679. By assuming a deflecting angle, α, lower than 2° and a dipole magnetic length, *l*, of about 60 cm, being $\alpha = l/\rho$ for ρ of about 17 m a dipole magnet of B=0.1 T is needed. An evaluation of the excitation currents needed to produce such a magnetic field can be done by assuming as first approximation a C-magnet type dipole. In that case, the total excitation current can be approximated by the relation: I_{tot}=2NI[Amp]=1/(0.4π)×B[G]×h[cm], for h=10 cm (as could be for a O-magnet dipole). Consequently, a total excitation current of about 4100 A×Turns [AT] is needed. It is worth mentioning that the equations above used to evaluate the dipole parameters are valid for a C-magnet dipole, while we are proposing the use of an O-magnet dipole for which some approximation are no longer valid. In order to evaluate the O-magnet dipole parameter values, with a better precision, a computer code has been used for the magnetic field calculation.

The O-magnet for the BDS of AMIDERHA, in fact, has been designed by using the electromagnetic module of the COMSOL code (Manual 4.4, 2016). Figure 1 shows a COMSOL model of the proposed dipole. As a first step the dipole parameters found above have been used: dipole length and height of 60 and 10 cm, respectively. At the end an excitation current of 7500 [AT] (I= 150 N=50) instead of 4100 [AT] has been used in the simulation. This is expected since, as already noted, the excitation current for an O-magnet dipole is less efficient than the C-magnet type. The results of the magnetic field calculations for the model of Fig.1 are shown in Fig. 2, where the magnetic field lines and the magnetic flux density (in [T] on multislices) are shown. In the simulation of Fig. 3, the proton beam particle trajectory calculated by using the dipolar magnetic field of Fig. 2 is presented. It shows that the dipole field used could deflect the150 MeV proton beam of AMIDERHA up to 1°. Furthermore, the deflection angle obtained in that simulation was underestimated because the calculation considered the proton trajectory along the dipole length alone, while the effect of the magnetic tails was not considered.



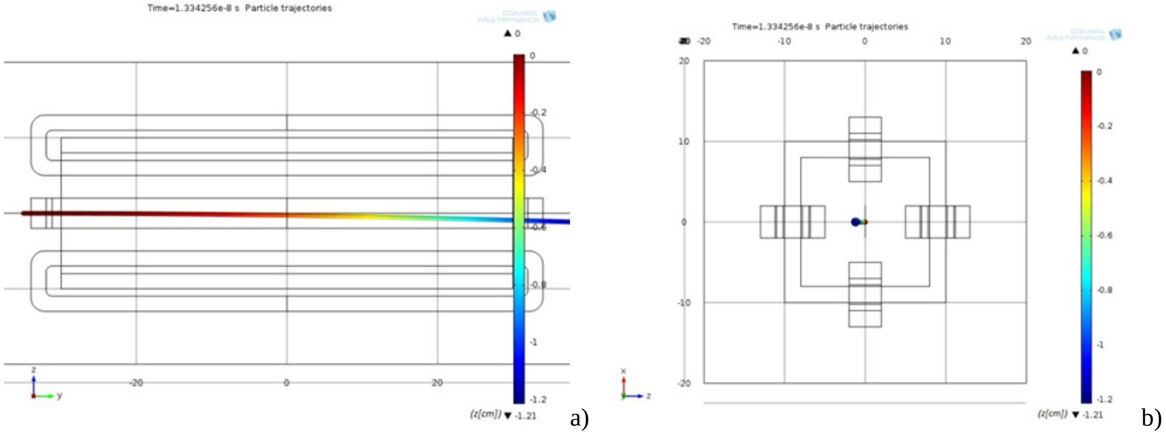
a) b)

Figure 2. Magnetic field generated by the horizontal coils: a) a 3D view of the magnet, b) transverse plane at the center of magnet. The dipolar field can be noticed in the center.

The proton beam deflection simulation of about 1° obtained with COMSOL could allow with a SAD of 6 ÷ 7 m a squared scanned surface with a side 20 ÷ 24 cm (instead of the required 40 ÷ 50 cm).

This preliminary simulation results have confirmed, as expected, that because of a lower excitation current efficiency, the excitation currents of 7500 [AT] evaluated above resulted in a beam deflecting angle of only about

1°.



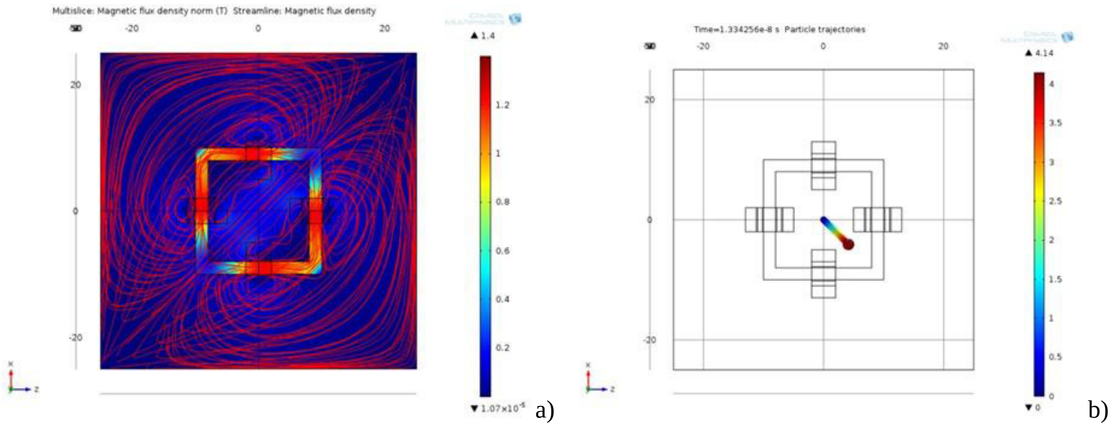
Time=1.334256e-8 s Particle trajectories

a)

b)

Figure 3. Proton beam deflection simulation in the horizontal plane: a) yx- plane view; b) xz-plane view.

The required deflecting angle of about 2° could be, however, obtained by doubling the excitation currents or by increasing the magnet dipole length, or finally by suitably changing both of them. In fact, from one side a doubling of the excitation current value could introduce cooling problem to the coils, while on the other side a doubling of the magnetic length could give a high off axis beam position in the trajectory at the end of the magnet.



Multislice: Magnetic flux density norm (T) Streamline: Magnetic flux density

Time=1.334256e-8 s Particle trajectories

a)

b)

Figure 4 Magnetic field lines and flux density [T] for an excitation current, NI= 13200 [AT]. In this case the excitation current is applied in both horizontal and vertical coils and a deflecting angle of 1.6° in both directions is obtained.

The maximum deflecting angle obtained with the simulations shown in Fig. 4, where the excitation current used was 13200 [AT,] has been more than about 1.6°. That angle with a SAD of 7 m could give a scansion in both directions of a side of ± 20 cm (corresponding to a squared scanned surface of 40 cm i.e. practically the value required by the AMIDERHA BDS).

The coil geometry used in our ‘steering magnet’ model shown in Fig. 1 has a transverse section of 8 cm^2. The number of necessary wire turns depends on the wire transverse section. In general, for current density lower than 2 [A/mm^2] an air cooling is used. For higher values, up to 10 [A/mm^2], a water cooling system could be enough. In our case, by using a water cooling system, a NI=8000[AT] could be reached, which is lower than the excitation current used in

Fig. 4. In order to allow higher excitation currents, the transverse section of the coil geometry of Fig. 1 has been re-designed by increasing the transverse section up to 15 cm^2. The new simulations carried out with the new excitation coil parameters have confirmed the results of Fig.4.

3. Conclusion

Recently the AMIDERHA project for pediatric proton therapy has been funded in South Italy (near Bari). The AMIDERHA Beam Delivery System (BDS) design included a pencil beam scanning system which would consist, essentially, of a unique magnet device to deflect the beam in both horizontal and vertical direction instead of the two usual magnet dipoles. In this paper the preliminary design of the unique magnet device capable of steering the beam in both horizontal and vertical direction has been presented and discussed. The simulation results have confirmed that for small deflecting angles (< 2°) a unique O-magnet dipole with coils in horizontal and vertical plane can be used for the proton beam scanning in both directions.

Acknowledgements

The work of F. Colamaria, D. Colella and M. Mastromarco have been supported by the Italian PON “Ricerca e Competitività” 2007-2013, project n. PON02_00576_3329762 with acronym AMIDERHA..

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