Review Article

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Unique Beam Scanning Device for Active Beam Delivery System in Proton Therapy

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ABSTRACT

A new Beam Delivery System (BDS) has been proposed for a proton therapy project, partially funded, called AMIDERHA. That BDS is characterized by an active scanning system which irradiates target with a pencil beam. The feature of this project was the using of an accelerator Linac with variable final energies and the Robotized Patient Positioning System instead of the traditional gantry. The active BDS of AMIDERHA then does not include a gantry and a pencil beam scanning system with a relatively long Source to Axis Distance (SAD) could be used. In this condition, the using of a unique device capable of scanning the beam for both horizontal and vertical plane in the active BDS of the project is possible. In this contribution this new beam scanning device will be presented. Furthermore, a preliminary design of the device and the trajectory simulations for beam parameter optimization will also be discussed.

Introduction

Few years ago, a new hydrotherapic center, named AMIDERHA, has been partially funded for operating in the South-Italy [1]. More recently the AMIDERHA project obtained new funds to complete the project. That considers new solutions for hadron therapy treatments: the accelerator to be used is a LINAC that can deliver variable beam energy between 70 and 150 MeV and the gantry will be replaced by the using of a positioning system of the patient – bed block.

The AMIDERHA Beam Delivery System (BDS) is characterized by a dedicated transport channel capable to deliver a beam of different energies coming from the LINAC, a unique magnetic scanning system device capable of scan the system in both horizontal and vertical planes and by a Robotized Patient Positioning System (RPPS). The transport channel and the scanning system allow the protons to reach the tumor target and release the right radiation dose on an extended volume. The design of the channel allows the beam to hold its pencil beam shape, i.e. a diameter smaller than about 7 mm [1]. Although the beam is fixed, the RPPS allows, in principle, a complete tumor treatment in any part of the body patient thanks to the properly moving 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 [1]. At NIRS – HIMAC in Japan a similar project, still under development, will also provide a treatment where the patient has to be handled at the right, giving way completely the gantry [2].

The BDS beam transport channel will consist of focusing elements, such as quadrupoles, bending magnets to drive the beam at the treatment room, the magnetic beam 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. That preservation could be done by slightly changing the bending field and the strength of few quadrupoles.

The beam transport design simulation for proton beam with energy of 150 MeV has been carried out by TRACE 3D code [3]. It has allowed us to find the right quadrupole gradient values and of 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 [4]. 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 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 at the beginning of the last drifts. The beam scanning magnetic system consists, usually, of two bending magnets one for the particle scanning in the horizontal plane the other in the vertical one. 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 that proposal along with a preliminary design is presented, furthermore, trajectory simulations carried out to optimize beam parameters are discussed.

The scanning magnet system

The BDS with pencil beam scanning, currently, offers the best flexibility for shaping the dose distribution. The scanning magnets 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 kind of beam scanning technique have been proposed and used: the 'raster scanning' [5] and the 'spot by spot scanning' [6]. Both the techniques use two dipole magnets one for the horizontal plane and the other one for the vertical plane deflections. 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 instead the electromagnet currents are controlled in such a way that for first is applied a horizontal scansion for the whole extension of the tumor then the proton beam is lowered vertically and starts a new horizontal scansion up to cover the whole transverse surface interested by the tumor. In ref. [7] The scanning techniques have been demonstrated to be more efficient than the passive dose distribution and in the last years they have been largely applied at the BDS of proton therapy centers [8,9]. The beam scanning along the depth of the tumor is realized by the proper variation of the beam energy.

Both the scanning systems need of two dipole magnets for the beam deflection in the horizontal and vertical plane. The standard magnetic dipoles used for the beam transport of charged particles usually are designed to bend a beam of certain energy for a fixed angle. The dipole magnet of a scanning system, instead, must deflect the charged beam to variable angles also with different sign. For that reason, the using of standard dipole magnets is not allowed and proper deflecting angle devices have to be designed. The design must fulfill the constrains to keep the pencil beam quality 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 mm mr*) and a circular spot with a diameter lower than – *7 mm*.

In ref. [10] the possibility of using a unique magnet to deflect a pencil beam in both vertical and horizontal plane has been proposed and discussed. In this paper the proposed device is presented again with several beam trajectory simulations which confirm that it is suitable to be used as beam scanning device in an active BDS for an Adrotherapic center that uses a long Source on Axis Distance (SAD). In that reference a beam deflecting device followed by a SAD of 6 m was proposed for the AMIDHERA project which considered as first step proton beam energy of 150 MeV, for pediatric proton therapy, but with a plan to reach the 250 MeV needed to complete all the possible depths of tumors inside adult bodies.

As discussed in ref [10], the low values of the deflecting angles requested in the beam scanning for dose delivery system with long SAD give us the possibility of using a unique magnet of window-frame type (O-Magnet) with horizontal and vertical coils capable to steer the beam both in vertical and horizontal direction (see figure: 1).

The constrains given by the AMIDERHA project was a proton beam energy of *150 MeV* (for pediatric proton therapy as first step), a SAD of *6 m* and a squared scanning surface with a side of *40 cm* then a deflecting angle lower than *2°* (35 *mr*) should be enough.

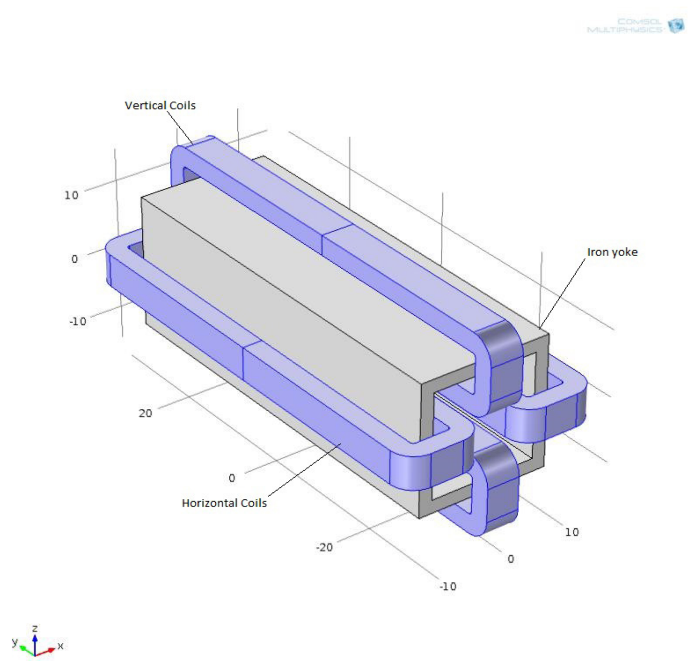

Figure 1: Dipole O-magnet type with horizontal and vertical coils to deflect charged beam both in horizontal and in vertical direction.

The magnetic rigidity R can be expressed [11] in *Bρ[Tm]* = 3.3356 *x p [GeV/c]* then for a proton beam energy of 150 MeV, which means *p = 0.53 GeV/c* (being p=*Eβ/c*), *R=1.7679*. In our proposal a deflecting angle, *α*, lower than 2° and a dipole magnetic length, l, of about 60 cm, has been assumed. Being *α = l/ρ*, for a curvature radius, *ρ*, of about 17 m a dipole magnet capable to give a B=0.1 T is needed. The evaluation of the excitation currents needed to yield that 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 [11]: $I_{tot}=2NI\ [Amp]=1/(0.4\pi)\ x\ B[G]\ x\ h[cm]$, for h=10 cm (as it could be for a O-magnet dipole) the total excitation current will be about 4100 AxT. It worth to notice that since the above equations used to evaluate the dipole parameters are valid for a C-magnet dipole but will be used an O-magnet dipole, the approximated results are obtained. In order to evaluate with a better precision, the O-magnet dipole parameter values, the COMSOL computer code [12] 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 and in figure 1 it is shown the dipole model used. As first step the dipole parameters found in the above rough calculations have been used: dipole length *60 cm*, dipole height *10 cm*. At the end, the excitation current used in the final simulation has been *7500 [AT]* (*I= 150 N=50*) instead of the above computed *4100 [AT]* because the excitation current for the O-magnet dipole is less efficient with respect the C-magnet type.

The COMSOL simulations shown in ref. [10] have allowed to determine the magnetic field of the deflecting device and, in particular to find the required excitation coils but a very high current density ($J=937.5\ A/cm^2$, very close to the maximum limit of $10\ A/mm^2$ [13]) was needed in that condition. In order to allow the using of so high excitation currents with more reasonable current density, the transverse section of the coil geometry has been re-designed by increasing the transverse section up to 15 cm^2 (instead of the 8 cm^2 of fig. 1) in this way a larger excitation current could be applied with lower current densities. The magnetic fields obtained with this new configuration is shown in fig 2 for the case, *I=70 A* and *N=100*. Those magnetic fields have been used in the pencil beam simulations shown and discussed in the next paragraph.

Beam trajectory simulations

In an active beam delivery system, a pencil type beam with high quality has to be used. That means, small beam spot size (few *mm*) and very low beam divergence (˷1 *mr*) furthermore they should have an emittance ε (where ε is roughly given by the product of the transverse beam size and the beam divergence) of the order *1 mm·mr*. As mentioned above the AMIDEHRA BDS will have a long SAD and it means that there will be a long drift region without focusing elements (in our case 6 m) which makes the constraints on the beam emittance ε also more stringent. A beam spot size lower than *7 mm* (FWHM) [13] is required, in fact, also after that the beam has travelled all along the SAD and arrived on the tumor volume.

In the beam dynamic calculations, the Twiss parameters α, β and ε are usually used to characterize the particle beam features [14]. In the beam transverse phase spaces, *(x, x')* and *(y, y')* the beam is represented by an ellipse with a constant area given by ε, a beam transverse size $x\ (y) = (\beta_{x(y)}\ \varepsilon)^{1/2}$, which in the case of a circular beam spot coincide with the beam radius and the beam divergence given by $x'\ (y') = [(1+\alpha^2)\ \varepsilon/\beta]^{1/2}$.

When a beam scanning system is used, the last beam focusing elements, needed to keep the beam spot size very small must be placed just before the beam scanning system. In fact, after the scanning device the beam goes off the central axis while the magnetic elements, used to focus the beam, act properly only on the symmetry axis. Since in our case the beam target (the tumor volume) is placed after a SAD of about *6 m* the beam should travel for *6 m* without focusing elements. The focusing strength and the initial beam parameters must be chosen in such a way to preserve the beam quality of the beam, that is, beam spot size of about *6 ÷ 7 mm* and minimum beam divergence. Beam envelope simulations for different focusing strengths and initial beam parameters have been carried out with TRACE3D in order to find the best beam conditions at the end of the *6 m* drift space. The results are shown in figure 3, where a quadrupole triplet has been used to keep the beam quality required. The quadrupole triplet has been chosen to make the focusing action much more symmetric between the vertical and horizontal planes. It consists of three quadrupoles uniformly spaced with equal magnetic fields. The 2 end quadrupoles are of equal length and the central one is twice the length of either of the end ones. From the simulation results of figure 3, it can be noticed that the beam envelopes have lower final beam spot sizes for higher focusing strengths but, in this case, also the beam divergence increased, then a tradeoff should be find to minimize the beam spot size on the tumor. The best choice seems to be the case with magnetic gradients *B'o* (external quadrupoles) of *21 T/m* and *B'i* with *-21 T/m* (inner quadrupole).

It must be noticed that in the TRACE3D simulations beam energy of 250 MeV has been used. That energy, in fact, should be the final goal of the AMIDERHA project, since 250 MeV energy allowed a proton beam to reach the deepest tumor in an adult body.

A more realistic simulation can be obtained if, instead of calculating the beam envelope, the trajectories of a particle distribution are computed. In figure 4, the proton trajectories simulation for a beam of 250 MeV energy carried out with COMSOL is shown. In that simulation the beam scanning modelled as in figure 1 is considered. The excitation currents applied produced a beam deflection angle in both planes of about 1.24°. The initial beam ellipse parameters of the transverse phase planes used in the COMSOL simulation have been given in the TRACE3D simulation of figure 3, after the first element (the quadrupole triplet) before the 6 m drift length. In figure 4, furthermore, a parabolic particle distribution in the transverse phase plane has been used for a beam with an energy spread of 1%. In figure 5, the initial (before the deflecting magnet) and final (at the end of SAD) particle distributions are shown for

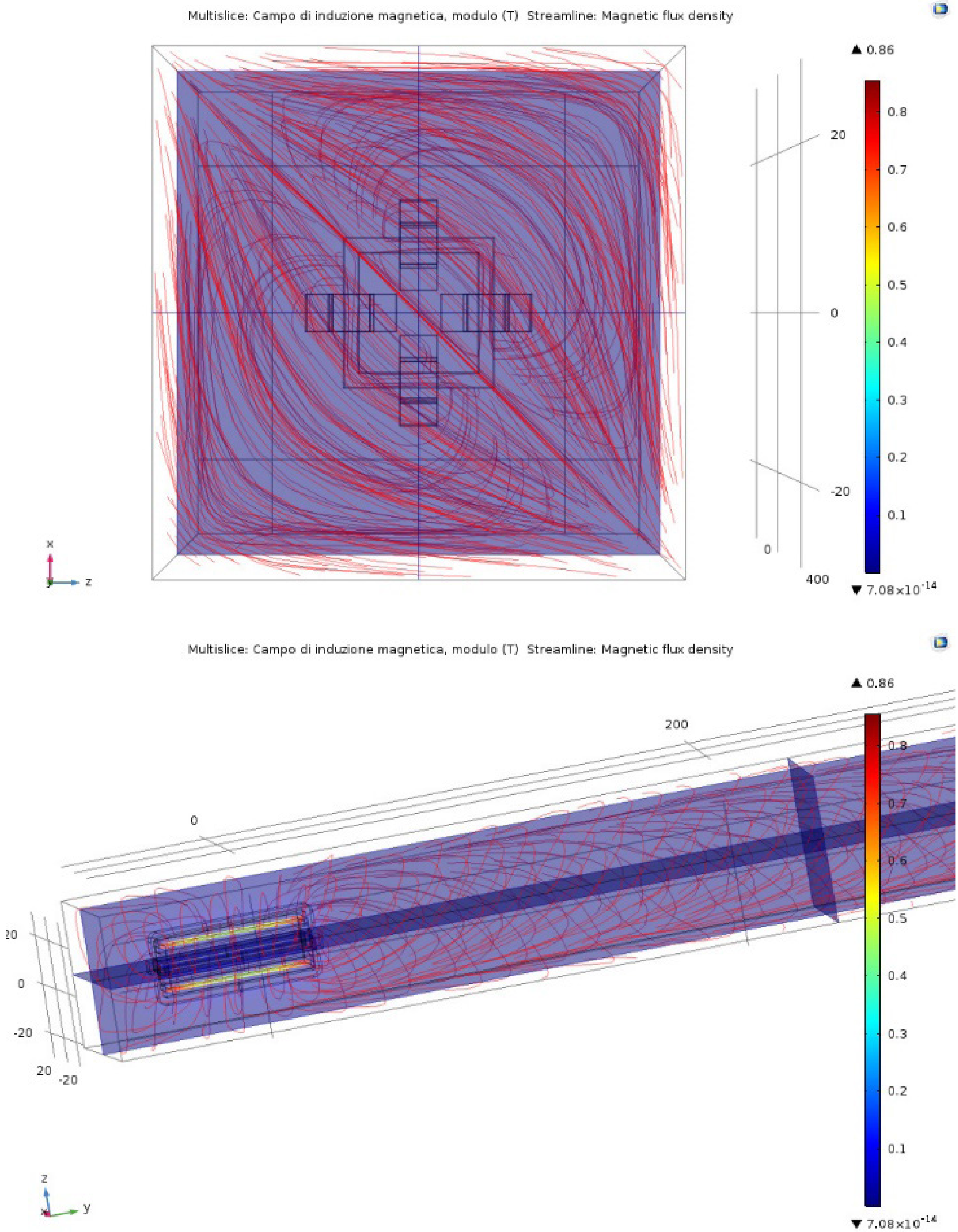

Figure 2: Magnetic field lines and flux density [T] for an excitation current, NI= 1400 [AT] in both horizontal and vertical coils: a) magnetic flux lines projection on (x,z) plane; b) magnetic flux lines in a 3D view.

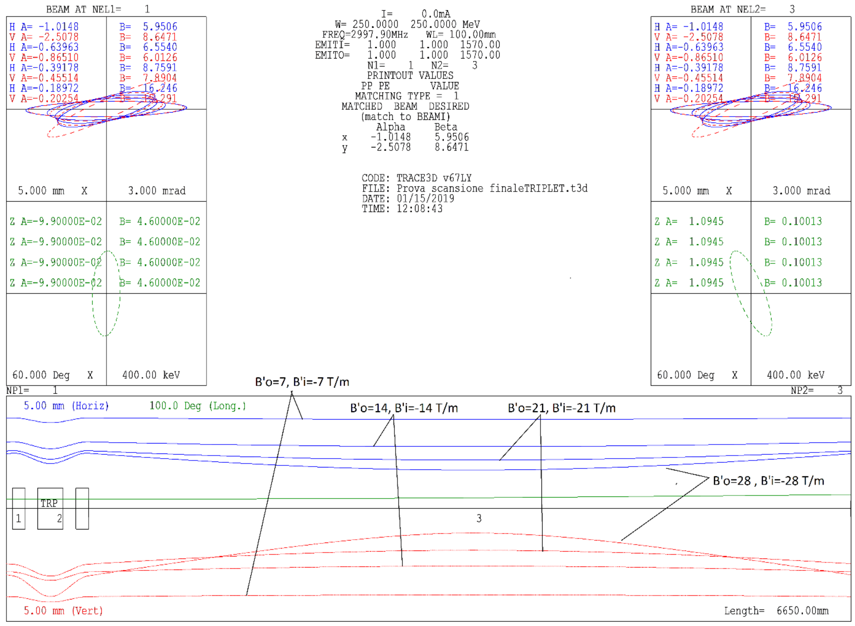

Figure 3: In the upper part of the figure, the initial and final phase space beam ellipses are shown; in the lower part the beam envelopes along z for different quadrupole focusing strengths. The element 2 is a quadrupole triplet (with *B'o*, outer magnetic gradient, *B'i* inner magnetic gradient) and the elements 1 and 3 are drift spaces. Notice that for each focusing strength a new matching for the initial and final beam parameters have been computed.

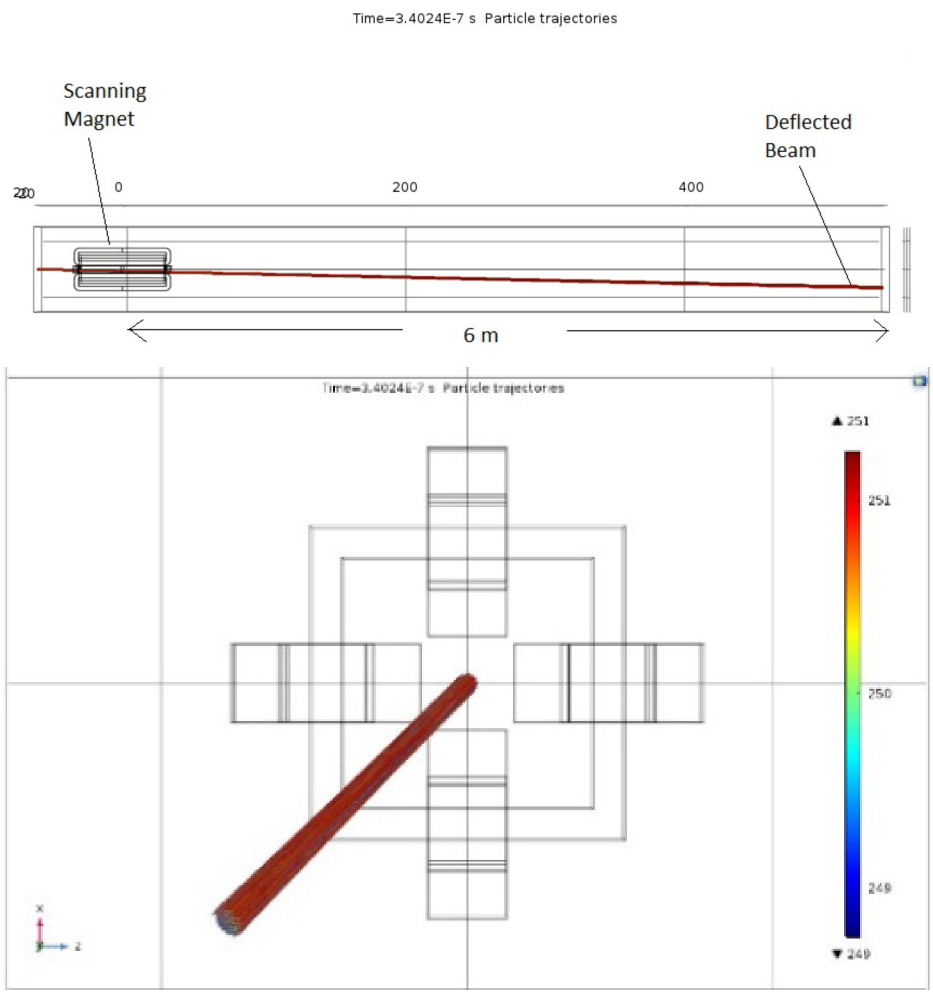

Figure 4: Proton beam trajectories for a SAD of 6 m and a beam energy of 250 MeV. The beam ellipses (Twiss) parameters used are: $\alpha=0.6$; $\beta=7\ m$ and $\varepsilon=1\ mm\ x\ mr$. On the left the (x,z) plane; on the right the (x,y) plane.

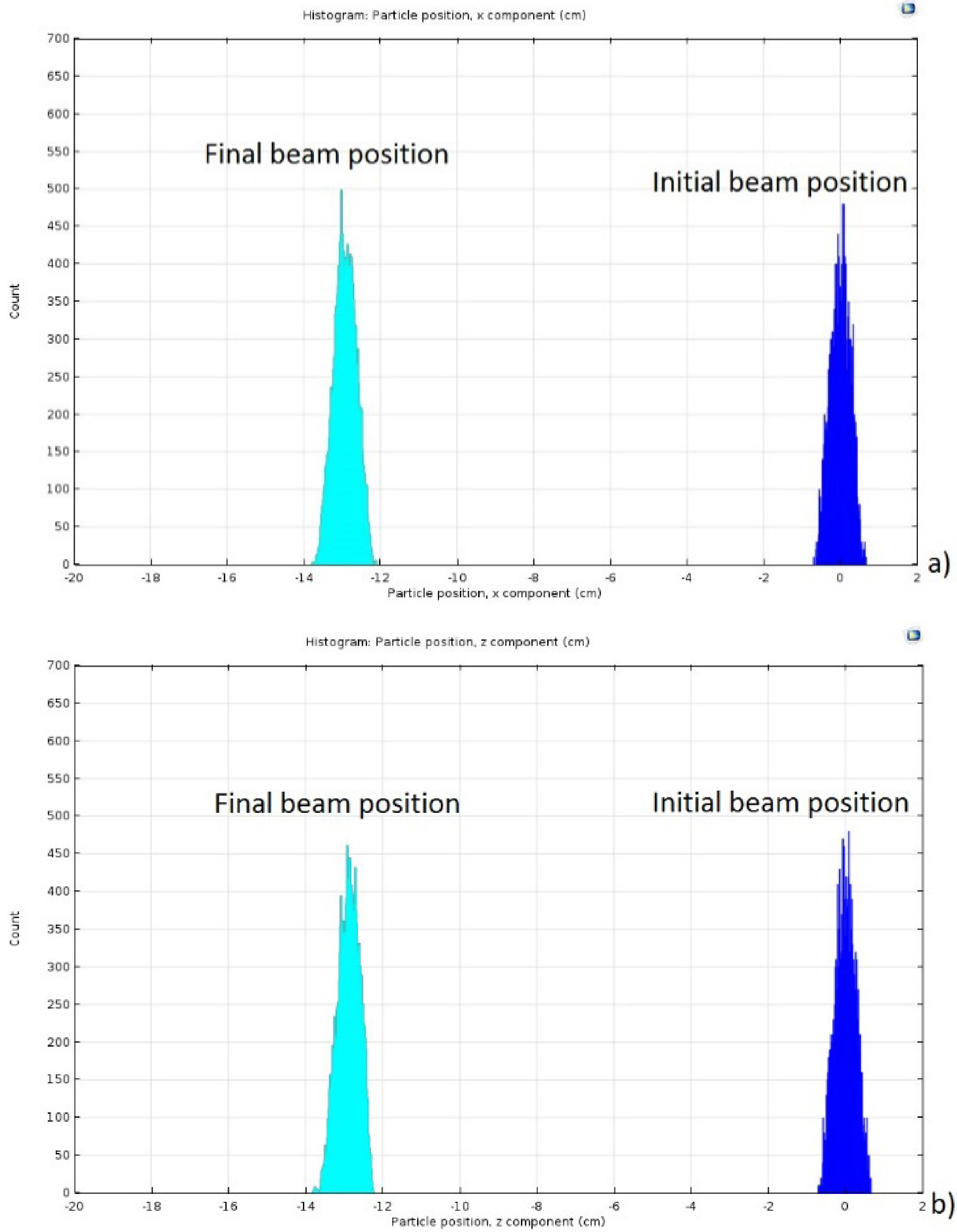

Figure 5: Histograms of a beam particle distribution with no energy spread and α=0: a) in z direction b) in x direction. The 'initial beam' indicates particle position before the bending magnet, 'deflected beam' at the end of the SAD (final distribution).

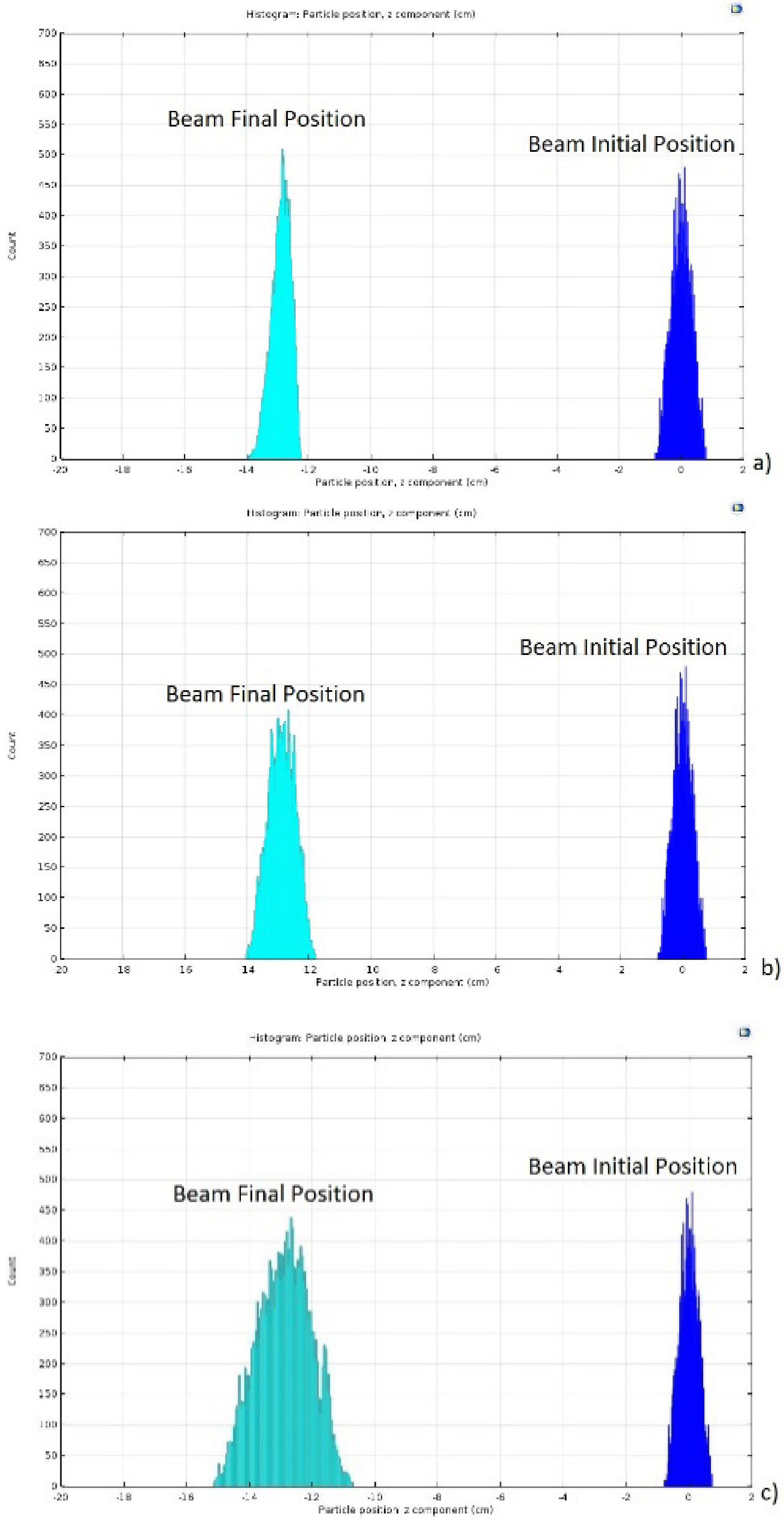

Figure 6: z-direction beam particle distributions: a) with the beam parameters increase of 5%; b) with beam emittance, ε =*2 mm mr*; c) with beam emittance, ε =*4 mm mr*.

the case of figure4, where an emittance, ε, of *1 mm mr* with beam radius of *3 mm (FWHM)* and energy spread of *1%* are used.

From the results shown in figure 4 and figure 5, it can be noticed that the final (deflected) beam keep good quality confirming the beam envelope simulation results of figure 3. In other words, by using the initial beam condition obtained by TRACE3D simulations for the case with *B' =25 T/m* the initial and final beam spot keep practically the same sizes.

The very good final beam quality of figure 4 and 5 have been obtained by using the best beam initial conditions given by the parameters computed in the TRACE3D simulations shown in figure 3. The final beam spot will change, of course, for different beam initial conditions. In order to give an idea of how the final beam spot is sensitive to the beam initial parameters changes further particle beam trajectory simulations have been carried out. In figure 6, a simulation with different beam initial parameters have been shown. In the simulation of figure 6a) the beam parameters (α, β, ε) have been increased of about 5%. It seems that for those light changes the final beam quality changes very slightly. On the other hand, the using of a low value of the beam emittance is important as it can be seen by the simulation results of figures 6b) and 6c) where cases with doubled and tripled emittances are shown.

Conclusion

Few years ago a project for pediatric proton therapy, called AMIDERHA, has been funded in South Italy (near Bari). The AMIDERHA Beam Delivery System (BDS) design included the proposal of new 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 scanning magnet dipoles. In this paper the preliminary design of the magnet device capable of steering the beam in both horizontal and vertical direction has been presented and simulated. The simulation results have confirmed that for small deflecting angles (< *2°*) a unique O-magnet dipole device with coils in horizontal and vertical plane can be used for the beam scanning in both directions. Further, the COMSOL simulations have shown that to obtain a maximum scanning size of *40 cm* (± *20*) at *6 m*, excitation currents of *10500 [AT]*, which require current densities of $700\ A/cm^2$, are needed.

The beam envelope simulations carried out with TRACE3D and the beam trajectory simulations carried out with COMSOL, have allowed to find the best beam parameters and so to obtain the smallest beam spot at the end of the SAD, on the tumor volume. COMSOL simulations showed also that a small change of the beam parameters, within the 5%, practically did not change the final beam spot. However, beam emittances with a factor 2 or more than the used emittance of ε =*1 mm mr* increased sensitively the final beam spot after the SAD spoiling, in this way, the pencil beam scanning performance.

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