HIGH ENERGY TRANSPORT LINE ORBIT CORRECTION AT CNAO

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Abstract

CNAO is the only Italian facility for the cancer treatment with protons and carbon ions. Each treatment needs hundreds of energies in the range of the tumour depth and needs a great precision in terms of beam position and divergence at the target. The goal of the article is to show the layout of the CNAO high energy transmission lines and the strategy that has been used to optimize the transport and set the beam trajectory.

BEAM DELIVERY AND CNAO MACHINE

Hadrontherapy is the use of ions (typically protons and carbon ions) to irradiate tumour cells. There are essentially two techniques to shape beam distribution on the tumour target: passive and active beam delivery. The passive delivery consists in changing beam characteristics by means of several absorbers put before the patient. On the contrary in the active delivery method two magnets ("scanning magnets") are used to move the beam in the two orthogonal directions. In the active scanning the tumour is virtually divided in slices in the longitudinal direction and each slice is thought as composed of small volumes called voxels: each slice is irradiated fixing the beam energy and each voxel is aimed at by changing the currents of the scanning magnets.

Active scanning has several advantages with respect to passive scanning as explained in [1].

CNAO is one of the few facilities in the world able to treat cancer using both high-energy protons and carbon ions with active beam delivery. At CNAO, ion beams are generated by two ECR sources, pre-accelerated by a 7 MeV/u LINAC, accelerated by a 77 m synchrotron and delivered to three treatment rooms, two lateral rooms equipped with a horizontal line and one central room equipped with both a horizontal and a vertical line. Beam is extracted from the synchrotron to the high energy transfer line (HEBT) by a slow extraction mechanism [2]: beam is driven to a third order resonance by a betatron core and "captured" by an electrostatic septum and three magnetic septa. At the end of each line, one strip and one pixel chamber work as dose delivery [3] system that monitor the dose delivered to the patient and control the two scanning magnets that are able to displace the beam over a surface of 20x20 mm^2 at the *isocenter* (i.e. where the patient is positioned). Proton are extracted in the 60-220 MeV energy range, corresponding to a penetration in water of 30-320 mm; carbon beams are extracted in the 120-400 MeV/u energy range corresponding to a penetration in water of 30-270 mm. Considering that the clinical energy step is 2 mm, treatments required the commissioning of 146 proton beam energies and 124 carbon ions beam energies.

CNAO HEBT LAYOUT AND CONSEQUENCES ON BEAM

The main trajectory of the beam in the HEBT [4] is the following: after the magnetic septa, 3 dipoles (*H-line dipoles*) make a 67.5° bend, then beam can go to the horizontal lines (*Z, T, U lines*) or the vertical line (*V line*). For the horizontal lines, the so called switching dipole, equipped with a three holes vacuum chamber, can direct the beam in one of the three horizontal lines. For the vertical line 4 dipoles (*V-line dipoles*), inserted before the switching dipole and after the 3 H-line dipoles, transport the beam to a height of 20m, where a single 90°, 130 ton dipole directs the beam to the central room.

Interlaced with the H-line dipoles, a fundamental element of the machine is installed: the HEBT chopper. Such device consists of four fast dipoles fed in series according to the scheme (+B, -B, -B, +B). When the magnets are switched off the beam strikes an obstacle (HEBT dump) avoiding irradiation of the patient. When the magnets are switched on, the beam is deflected allowing it to avoid the dump. The dose delivery system controls the HEBT chopper status according to the dose delivered to the patient: when a slice has been completely irradiated, it switches off the chopper.

In the horizontal lines the scanning magnets are positioned in the final part of the line 7 m far from the isocenter, without magnetic elements in between. In the vertical line scanning magnets are positioned before the 90 degrees dipole that is designed to transport in parallel the scanned beam.

Figure 1 shows the scheme of the whole machine with the four extraction lines.

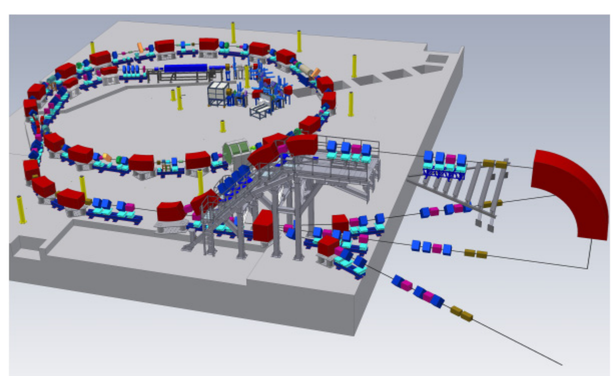

Figure 1: 3-D scheme of the whole CNAO machine, from the injector (inside the ring) to the 4 extraction lines.

Beam profiles can be measured along the HEBT by 21 monitors, named SFH and based on the scintillating fiber technology [5], that can be put in and out the beam path.

An SFH called QBM, is installed at the dump level: when QBM is in, it measures the beam that goes to the patient; when QBM is out, it measures the beam that dies on the dump. Checks on the beam are also performed at the isocenter thanks to a moveable strip chamber detector (*ministrip*).

The clinical requirement on beam position precision at the isocenter is generally of 0.1 mm. A feedback system [6] is implemented on the current of the scanning magnets to reach this precision. The input of this feedback system is the position measured in real time by the dose delivery monitors; since this is not a direct measurement of the position on the target, this approach works only if the beam divergence at the isocenter and at the scanning magnets is low for both planes (the so called *steering condition*).

Furthermore, the feedback correction is not instantaneous and while the correction is applied the beam is reaching the target in an incorrect position: to make the correction time negligible with respect to the treatment time the initial position must be not too far from zero. In our case, for treatments one can accept that, without correction, the beam position error is within ±0.5 mm at the scanning magnets and at the isocenter.

To guarantee this important constraint for the horizontal lines (Z, T or U), , position is set at zero at the SFH just before the scanning magnets and at the isocenter by using two horizontal and two vertical kickers. For the vertical line (V), because of the presence of the 90° dipole, the steering condition is fulfilled differently for horizontal and vertical plane: for the horizontal plane the criterion is the same as for the horizontal lines while for the vertical plane the beam position is set to zero at the SFH just before the scanning magnets, at the dose delivery monitor and at the isocenter by using two vertical correctors and the 90° dipole itself.

Using the beam profile measurements at the SFHs and the betatron functions obtained by the optic model (MADX) of the line, it is possible to calculate the beam envelope along the HEBT: this is useful to understand the impact of beam size and trajectory on beam losses.

$$Beam\ Envelope = K\sqrt{\varepsilon\beta}$$

Where K is a form factor depending on beam distribution, ε is the geometric transverse emittance and β is the betatron function. The factor $K\sqrt{\varepsilon}$ is obtained by fitting the measured data.

Figure 2 shows the vacuum chamber size and beam size along the H-line and T-line for horizontal and vertical plane: blue lines represent the vacuum chamber, black line is the beam barycentre, red lines are the beam envelope measured by the SFH and green lines are the beam envelope calculated fitting SFH measurements. Figure 2 shows that to avoid losses it is better to take beam trajectory in the range within 3 mm from the vacuum chamber center.

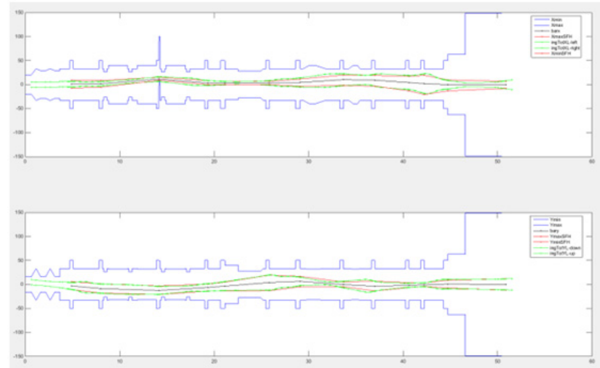

Figure 2: Horizontal and vertical beam envelopes (measured and theoretical) inside the vacuum chamber of the H line and T line.

Tumors at CNAO are irradiated starting from the lowest to the highest energy. Differently from the synchrotron magnets, HEBT power supplies don't have time to make a standardization cycle between two consecutive treatment energies. This puts a severe constraint on the values of the magnets for the various energies: in order to guarantee the repeatability of the magnetic field the trend of the power supplies current with respect to the energy must be monotonically increasing or decreasing (*monotonicity condition*). For dipoles and quadrupoles, the monotonicity condition is automatically fulfilled because the current is proportional to the magnetic rigidity of the particles; on the contrary for the kickers the condition must be carefully kept under control.

Correction of Vertical Orbit for Line T

The vertical orbit when all the vertical kickers are off depends only on the orbit in the synchrotron and on the residual field of the first V-line dipole. An accurate correction of the orbit in the synchrotron allows to reduce the beam distortion along the line, in particular at the position before the first V-line dipole. Figure 3 shows HEBT trajectory before and after synchrotron orbit correction for the lowest proton energy.

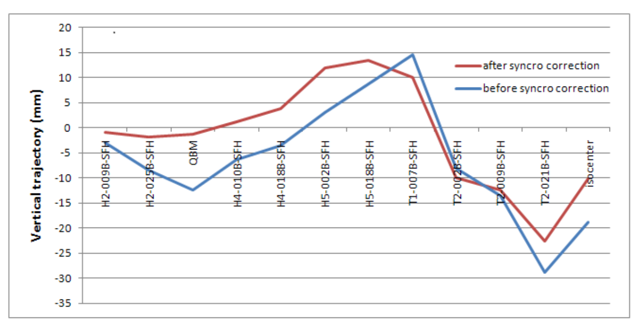

Figure 3: T line measured vertical trajectory before (blue line) and after (red line) synchrotron orbit correction.

The kickers chosen for the orbit correction are the one in a red circle shown in Figure 4: with this set of kickers we satisfy the monotonicity condition and guarantee a correction within 3mm for all the energies.

ISBN 978-3-95450-182-3

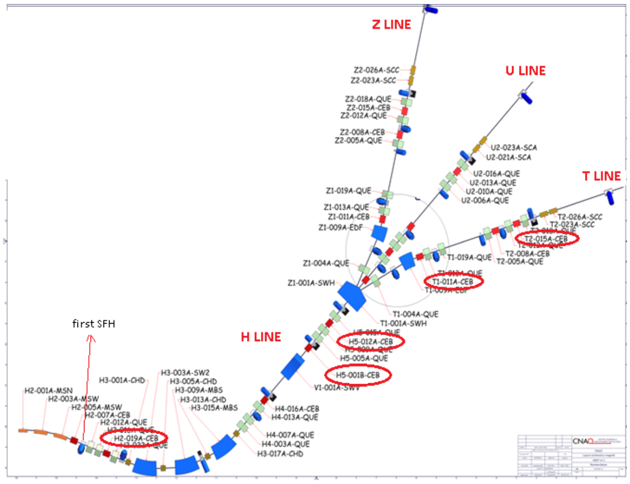

Figure 4: Magnetic and diagnostic layout of H line and T line. A red circle contains the vertical kickers chosen for the vertical trajectory correction.

The algorithm for the correction is the following: the currents of the last two kickers in the T line are obtained directly from the steering condition (mathematically this condition is a set of 2 equations with 2 variables) and then they depend on the current of the other 3 kickers and on the position along the line with all the kickers off. The current for the other 4 kickers is obtained minimizing the beam position at all the SFHs except for the last one that is used for the steering condition. The minimization is simply performed by a Matlab script exploiting the least square method. Figure 5 shows the result of the vertical plane steering.

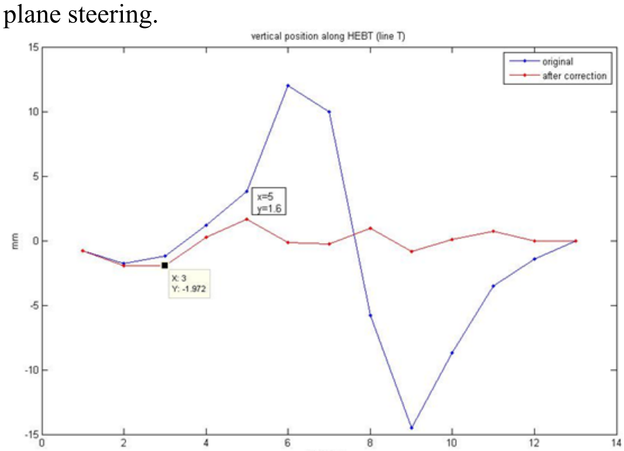

Figure 5: Measured vertical trajectory before (blue line) and after final correction (red line).

Correction of Horizontal Orbit for Line T

Horizontal correction is more complicated due to the presence of 5 dipoles along the line and HEBT chopper. The criterion is to use the extraction magnetic septum and the first kicker between the first two SFHs to enter in the first dipole with zero angle and position. Then, one can calculate exactly the current of the three dipoles and of the HEBT chopper for a centred orbit using the following information: the position at the two SFHs after the third dipole, the position at QBM when it is out and the HEBT chopper is off and the position at the QBM when it is in and the HEBT chopper is on. Similarly to the vertical orbit, two horizontal kickers in the line T (the same magnets used for the vertical plane) are used to satisfy the steering condition; the horizontal kicker after the V-line dipole, the switching dipole and the dipole of the T-line are set to minimize the position along all the SFH except of the last one. Figure 6 shows the horizontal trajectory before and after the correction.

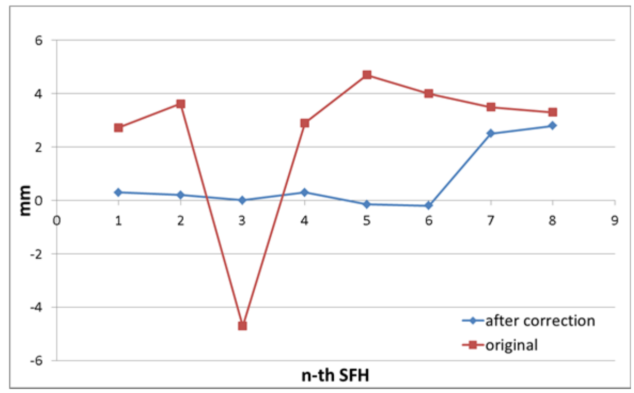

Figure 6: Horizontal trajectory before and after correction.

CONCLUSION

CNAO treats patients successfully from 2011. The beam quality at the isocenter is a fundamental issue for the treatment quality; the transport of the beam through the extraction lines represent then an important task for the treatments and for the beam transmission. Dedicated algorithms have been adopted to satisfy the trajectory requirements along the line.

REFERENCES

[1] L. Falbo, “Advanced accelerator technology aspects for hadrontherapy,” in *Proc. HIAT’11*, Chicago, USA, 2011, paper WEA01.

[2] P. J. Bryant *et al.*, “Proton Ion Medical Machine Study (PIMMS) Part 1 and 2,” CERN/PS 1999-01-DI (1999) and CERN/PS 2000-007- DR, Geneva (2000).

[3] M. Donetti, “Design and characterization of the beam monitor detectors of the Italian National Center of Oncological Hadron-therapy (CNAO),” *Nuclear Instruments and Methods in Physics Research A*, vol. 698, pp. 202–207, 2013.

[4] E. Bressi *et al.*, “Optics of extraction lines at CNAO,” in *Proc. IPAC’12*, New Orleans, USA, 2012.

[5] E. Rojatti *et al.*, “Scintillating fibers used as profile monitors for the CNAO HEBT lines,” in *Proc. IPAC‘15*, Richmond, USA, 2015, paper MOPHA051.

[6] M. Donetti *et al.*, “Performances of the scanning system for the CNAO center of oncological hadron therapy,” *Nuclear Instruments and Methods in Physics Research A*, vol. 613, pp. 317–322, 2010.