OPTICS OF EXTRACTION LINES AT CNAO

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Abstract

The CNAO (National Center for Oncological Hadrontherapy), is the first Italian center for deep hadrontherapy with proton and carbon ion beams, treating patients since fall 2011. The beam is delivered to the patient through a high energy transfer line (HEBT). The line is equipped with a horizontal switching dipole that distributes the beam in three treatment rooms and a vertical switching dipole that allows a vertical delivery of the beam in the central treatment room. The CNAO HEBT commissioning has been carried out using proton and Carbon beams in the full range of energies: 60 to 250 MeV/u for protons, 120 to 400 MeV/u for Carbon ions. Optimization of the beam lines setup has been carried out for a few energies, applying beam magnetic rigidity scaling for the full range in steps of the order of 1 MeV. The scaling has proven to be satisfactory for most elements, and only minor adjustments were needed to fulfill tolerances in the whole range. Repeatability of magnetic settings is supported by measurements along the lines. Finally the results in terms of beam dimensions, beam transmission and beam position at the patient position are presented.

THE EXTRACTION LINES AT CNAO

Extraction is one of the most important parts of a medical machine. In order to accomplish medical requirements, the beam must be slowly extracted (few seconds) to facilitate the measurement and the control of the dose delivered to the patient.

At CNAO [1], the extraction is realized by the so called "resonant slow extraction mechanism". After the acceleration, the beam is driven to the third order resonance by a betatron. When the particle becomes unstable, it moves steadily outwards in the horizontal phase space until it "jumps" into the aperture of an electrostatic septum which gives the needed "kick" to extract [2]. This creates a strong asymmetry between the vertical plane and the horizontal plane for the extracted beam.

In the vertical plane the extracted beam has a bell-shaped distribution while in the horizontal plane, the beam is the portion of separatrix cut from the electrostatic septum and has a trapezoidal form (the so called “bar of charge”).

The simulation of the bar of charge in the empty ellipse also allows for an alternative method for adjusting the horizontal dimension; in fact, by varying the phase advance, also the orientation of the bar of charge varies and consequently its projection on the x axis, that corresponds to the horizontal beam dimension.

CNAO extraction lines can be divided into three parts:

- the line between the electrostatic septum and the thin magnetic septum;
- the initial external part of the line dedicated to the matching of the dispersion function;
- the final part leading the beam into the various treatment rooms.

A view of the extraction lines is shown in Fig. 1.

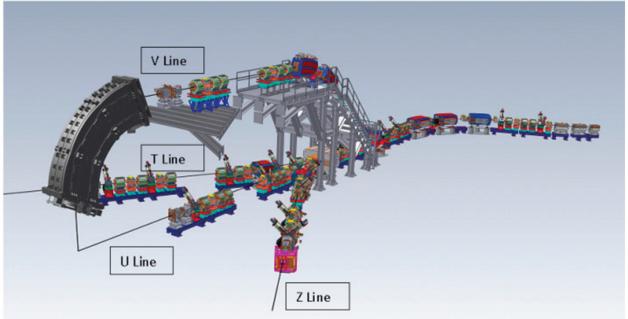

Figure 1: Treatment lines layout.

The part of the line between the electrostatic septum and the thin magnetic septum is internal to the synchrotron and the regulations in this part consist of a local bump obtained with five machine correctors. The bump adjusts the circulating beam in position and angle at the electrostatic septum and places the gap between the circulating beam and the extracted beam at the thin magnetic septum. The first external part begins with three magnetic septa, the first thin and the second two slightly thicker, powered in series.

In the first external common sector three dipoles are inserted, such that the dispersion invariant is reset to zero. Interlaced with these three dipoles there is a fundamental element of the project: the HEBT chopper. Such device consists of four fast dipoles fed in series according to the scheme (+B, -B, -B, +B). When magnets are switched off the beam strikes an obstacle avoiding irradiation of the patient (as shown in Fig. 2). The obstacle is also capable to measure the beam dimensions and intensity. When the magnets are switched on, the beam is deflected allowing it to avoid the dump. In this operation the beam remains on the same trajectory downstream the chopper and so remains correctly directed onto the patient.

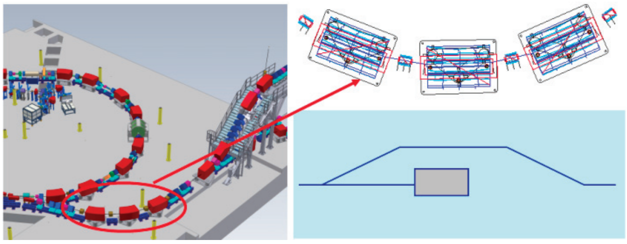

Figure 2: Chopper in the HEBT.

The chopper response time is less than 200 μs, which allows switching on and off the beam so as to administer less than 2.5% of the dose of a voxel, precision limit fixed by treatment planning tolerances.

The final part of the line is equipped with the so called switching dipole able to direct the beam in one of the three horizontal lines (named Z line, U line and T line); for the vertical line (named V line), beam is first transported from the synchrotron level to 6 meters height by four dipoles, then a single 90^0 dipole directs the beam to the central room isocentre.

At the end of the horizontal lines and before the 90^0 dipole in the vertical line, the horizontal and vertical magnets used for the active scanning technique are placed (the so called scanning magnets).

The lines are equipped with 24 beam diagnostics monitors, the so called SFH (Scintillating Fiber Harps) used for optics studies and measurements; at the end of each line there are the Nozzle chambers used to measure the dose delivered to the patient. For commissioning studies beam profiles were acquired with a strip chamber at the isocenter, i.e. the reference point for the patient positioning.

OPTICS STUDIES

Commissioning of the extraction lines has been carried out using the Z line for the transport of proton beams (from October 2010 to May 2011) and the T line for the transport of carbon beams (from January 2012 to April 2012). Presently line Z is used for patient treatment and line T for clinical and radiobiological commissioning of carbon beams [3]. By November 2012 all the lines will be commissioned with both the ion species.

The commissioned energy range has been 60-250 MeV/u for proton beams and 120-400 MeV/u for carbon ions. These energy ranges correspond to a wide excursion in magnetic rigidity (Bρ): indeed for proton beams Bρ goes from 1.165 to 2.312 and for Carbon beams it goes from 3.185 to 6.336. The commissioned energies have been 151 for protons and 122 for carbon ions giving respectively a set of penetrations in water from 30 mm to 320 mm and from 30 mm to 270 mm in water. The wide Bρ range and the wide number of energies made challenging the research of a scaling method for the setting of all the magnetic elements of the lines.

Quadrupoles

The starting point for the quadrupole currents has been the MAD [4] optics theoretical model giving the beta functions shown in Fig. 3 and the magnetic measurements for the relationship current-quadrupole gradient.

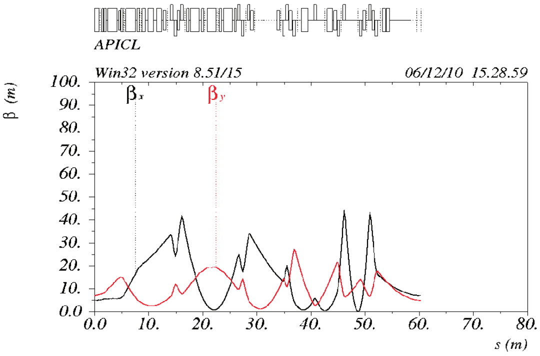

Figure 3: Theoretical optical functions evaluated with MAD8 along the HEBT in case of Proton beam.

To check these settings, profile measurements with SFH have been performed at the lowest energy of the whole energy ranges of both the ion species. Some minor adjustment have been needed to the settings of triplet currents just before the switching magnet in order to have a round beam at the end of the extraction lines and a FWHM of about 3.5 mm, which is the requested value for treatments. The quadrupole currents optimized at the lowest energies have been used to obtain the current for the whole energy ranges just rescaling the values with the magnetic rigidities. Particular care in the optics model has been given to the beam dimensions in the chopper region: in this region a small beam is needed to avoid the passage of radiation when the chopper magnets are switched off.

The emittance measurements are performed by quadrupole scanning method measuring the beam dimensions with SFHs. To extrapolate the optical functions from measurements a second order fit was used [5]. Fig. 4 shows an emittance analysis performed with data acquired in H4 section.

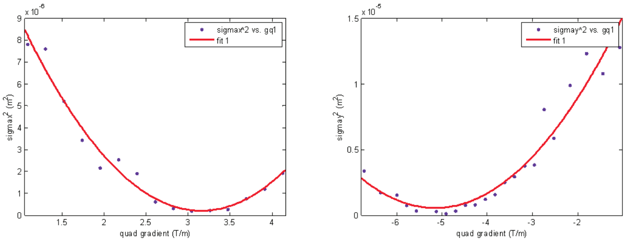

Figure 4: Parabolic fit performed with data acquired in section H4 for a Proton beam with an energy of 170 MeV.

An optical model which reasonably fits all significant measurements has been obtained with MAD8, with correction factors on the quadrupole gradients, with respect to the nominal calibration curve. These factors can be interpreted as a correction to the quadrupole calibration factor, or as a correction to the magnetic length or a beam energy higher than expected, or a combination of the three effects. In Fig. 5 the FWHM in both planes along the line for a 170 MeV proton beam is shown.

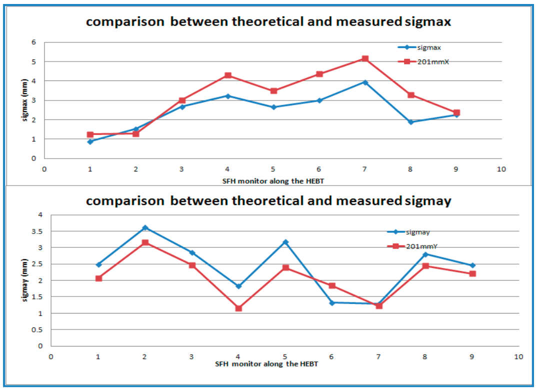

Figure 5: Comparison between beam dimensions measured along the HEBT and beam dimensions foreseen by theoretical model.

Bendings

The bending magnets of the line (electrostatic septum, magnetic septum, dipoles, kickers) have been set taking into account three constraints:

- The trajectory along the line must be optimized to avoid losses.
- Beam must pass through the scanning magnets centred in both the transverse planes and without divergence (X=X'=Y=Y'=0): otherwise the active scanning technique will cause beam to go in a wrong position at the patient.
- Considering that a treatment plan is made up of increasing energies, the magnetic elements must follow always increasing (or decreasing) values when the energy increases in order to avoid hysteresis loops affecting the repeatability of the magnetic behaviours.

Respecting only the three conditions above without the constraint of having the beam at the center of the vacuum chamber along the whole line has allowed to reduce the time needed to commission the beam and to reduce the number of kickers used along the line.

In the vertical plane, the beam trajectory has a weak contribution from the vertical orbit in the synchrotron; then it suffers of the residual fringe field of the first dipole of the vertical line, which is compensated by a vertical corrector before the switching dipole.

The horizontal trajectory is influenced by the slow extraction mechanism whose optimization causes the beam entering in the HEBT at different positions at the different energies. As a consequence the horizontal orbit adjustments has been more challenging and the approach for protons has been different than the one for carbon ions: the higher magnetic rigidity of carbon ions requires currents at which the dipoles have strong non linear behaviours and a reduction of the magnetic length. For both species, ten energies, giving ten equal steps in Bρ, have been studied to understand the scaling method to be applied.

For protons rescaling the bending elements currents with the magnetic rigidity has been quite effective; only a smooth steering with the electrostatic and magnetic septum to give a monotonic trend to the HEBT entrance (first two SFHs) was needed. On the contrary for carbon ions it was not possible to have an invariant value to be scaled with Bρ. In this case the method was based on the consideration that at each current I, the parameter:

$$K(E) = \frac{B_I(I) * \rho(I)}{B\rho(E)} \qquad (1)$$

where Bρ is the magnetic rigidity kinematically given by the beam energy (E); $B_I(I)$ is the function relating the magnetic field to the applied current and ρ(I) is the bending radius of the dipole, must be a constant. Therefore the current to be applied for the energy E is

$$I = B_I^{-1}\left(\frac{K(E)}{\rho(I)} B\rho(E)\right) \qquad (2)$$

For both the horizontal and vertical planes, the third condition is fulfilled thanks to the use of two horizontal and two vertical correctors placed after the switching dipole: a steering at the end of the line is realized using the constraints of a centred beam in both planes at the isocenter and at the SFH just before the scanning magnets. At these two monitors the transverse precision reached after steering with the kicker is less than 0.3 mm resulting in a divergence of the beam inferior than 0.09 mrad.

After optimizations, the transmission has reached values of the order of 70% , including the losses during the process of extraction. The beam intensity at the treatment rooms is about 4-5 10^9 particles per spill for protons and 1 10^8 for Carbon Ions, which is a value well matching treatment requirements.

CONCLUSIONS

Proton and Carbon ions beams have been transported in Z line and T line respectively. In the next months U line and V line will be commissioned and both particle species will be transported along all the lines in order to make operational all the lines for patient treatments.

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