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OPTICS AND COMMISSIONING OF THE CNAO EXPERIMENTAL BEAM LINE

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Abstract

CNAO (National Centre for Oncological Hadrontherapy) in Pavia is one of the six centres worldwide in which hadrontherapy is administered with both protons and carbon ions. The main accelerator is a 25 m diameter synchrotron designed to accelerate carbon ions up to an energy of 400 MeV/u and protons up to an energy of 250 MeV. It was designed with three treatment rooms and an 'experimental room' where research can be carried out. The room itself was built since the beginning, but the beam line was planned to be installed in a second moment in order to give priority to treatments. The beam line of the experimental room (XPR) is designed to be "general purpose", for research activities in different fields. In October 2018 the installation phase of the line was started and it ended in January 2019. In this paper a short description of the optics layout and commissioning strategy is given.

INTRODUCTION

The National Centre for Oncological Hadrontherapy (CNAO) in Pavia is one of the six centres worldwide in which hadrontherapy is administered with both protons and carbon ions [1]. CNAO was conceived since the beginning with three treatment rooms and an “experimental room”, where research can be carried on without hindering the clinical activity. Such an experimental room is designed to be “general purpose”, to be used for research in different fields. Possible activities could be, as an example, irradiation of cells, test of beam monitors and development of in-beam monitoring devices or radiation hardness studies [2].

The experimental room already exists, but it is not fully equipped. The present layout of CNAO beam lines is shown in Fig. 1 together with the modified regions.

Additional ion species are foreseen: light ions with $Z \leq 8$, starting with He, Li and O, will be available in the XPR. These species will be possibly produced by a dedicated third source. Larger ranges, for the species with lower atomic numbers, might be useful for some future R&D, like proton or helium radiography, and shall be considered in a second phase.

In addition, a specific automatic procedure that directs the beam to the experimental room during treatment pauses (i.e. when the accelerator is waiting to be used, like patient positioning procedures or interval in patient schedule) has been designed.

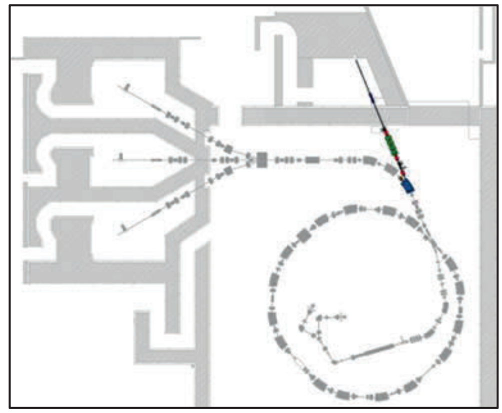

Figure 1: Layout of CNAO. Coloured the new implemented experimental line.

This automatic procedure cannot clearly be used in all the cases, because of the non-predictable duration of the irradiation, but, for the experiments in which the duration is not important and in which the measurement can be “paused” for an indefinite time, it can be a very convenient possibility.

MULTIPLE ISOCENTER

The beam distribution in the experimental room will be performed with the same active scanning system in use in the treatment rooms.

In order to make the best use of the available space, the part of beamline inside the XPR can be assembled in four configurations. In the first case, the beamline fully reproduces the clinical layout, with the irradiation point as downstream as possible, in order to get the maximum irradiation field (200 x 200 mm^2). The distance between the irradiation point and the rear wall is of 40 cm only (Fig. 2, panel A).

In the opposite case (Fig. 2, panel B), the irradiation point is just at the beam entrance into the room, leaving the maximum space downstream for TOF measurements; this configuration requires to remove the whole beam line starting with the scanning magnets. An intermediate irradiation position has been chosen as default, leaving almost 2 m free space downstream the irradiation point and still allowing an irradiation field of 135 × 135 mm^2 which satisfies most of the requests (Fig. 2, panel D). A fourth configuration, allowing beam monitoring in the most upstream position, completes the possibilities (Fig. 2, panel C).

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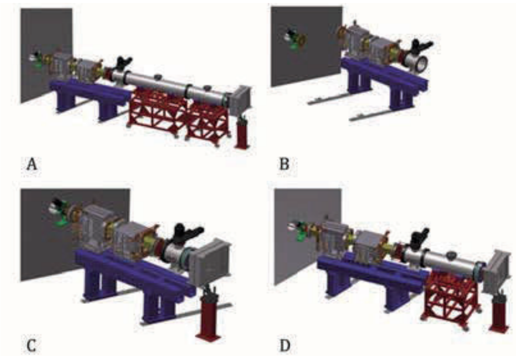

Figure 2: Beamline configurations in the XPR. Scanning magnets and nozzle are mounted on removable supports.

BEAM OPTICS AND BEAM MODEL

The beam is extracted from CNAO synchrotron by a third integer resonant slow extraction. In this type of extraction the circulating beam is brought close (in tune) to one resonance and then slowly pushed towards it, making it unstable and extracting a small fraction of the circulating particles at each turn.

Diverse can be the mechanisms of approach to the resonance, from the variation of the strength of one or more quadrupoles to the stochastic diffusion of the beam in longitudinal or transverse space-phases. In CNAO synchrotron this operation is performed by slowly accelerating the beam for induction through a "Betatron core" [3].

The particles in the unstable region move along three separatrices increasing the amplitude of oscillation turn after turn until they reach the electrostatic septum which deflects them towards the extraction line. In the horizontal phase-space, the beam is therefore constituted by the section of the separatrix cut from the electrostatic septum, called "bar of charge", and has very small emittance, as shown in Fig. 3.

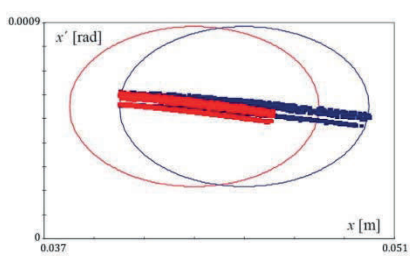

Figure 3: Bar of charge and empty ellipses for minimum and maximum $\Delta p/p$ of the extracted beam. The red bar of charge corresponds to $\Delta p/p$=-0.001 and the blue one to $\Delta p/p$=0.0.

CNAO beamlines were designed using the same approach used in PIMMS [3], considering an empty ellipse with emittance of 5π mm mrad, as shown in Fig. 3, and an initial dispersion defined by the spiral step and the corresponding momentum. Such an initial dispersion is matched to zero at the exit of the common bending section towards the treatment rooms.

In the case of the experimental room, the beam does not go through any dipole and the dispersion invariant $\gamma_x \cdot D_x^{\,2} + 2\alpha_x \cdot D_x D_x' + \beta_x \cdot D_x'^{\,2}$ cannot be matched to zero. It is possible to obtain D_x=0 or D'_x=0 at the irradiation position, but not both at the same time.

The beam transport to the XPR is conceived trying to reproduce a realistic situation and to be safely conservative, at the same time.

For this reason, most of the optical studies were performed considering as initial Twiss parameters those obtained in measurement campaigns, as summarized in Table 1.

Table 1: Initial Twiss Parameters from CNAO Measurements Campaigns

Twiss Parameters			
β_x [m]	9.07	β_y [m]	3.94
α_x [m]	0.22	α_y [m]	0.75
D_x [m]	0.34	D_y [m]	0
ε_x [π mm mrad]	0.49 (C^{12}) – 0.17 (P)		
ε_y [π mm mrad]	0.82 (C^{12}) – 0.68 (P)		

The resulting betatron functions are shown in Fig. 4.

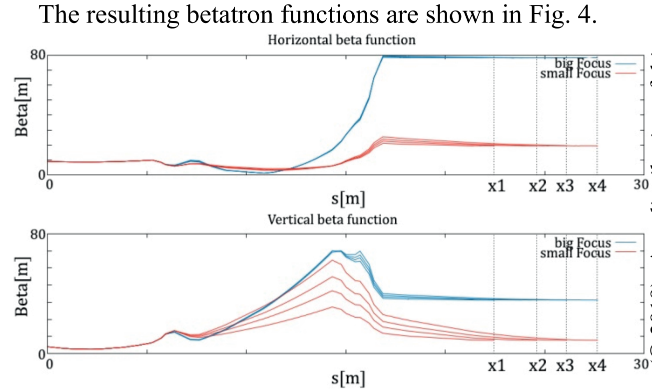

Figure 4: Betatron functions in the XPR beam line for small and large beam size at the four irradiation positions.

Besides Twiss parameters, beam positions and divergences, measured just before the XPR fork, are considered as input for the theoretical studies. Figure 5 shows the evolution of the beam trajectory for the four isocenters, starting from measured coordinates.

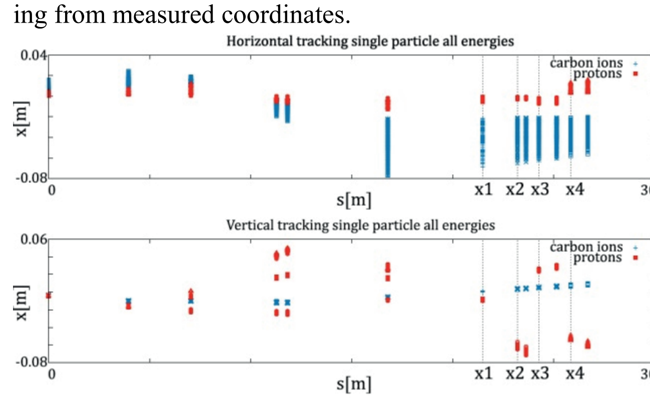

Figure 5: Tracking for both Protons and Carbon ions starting from measured beam position and divergence.

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CHOPPER MECHANISM

A very important element in the extraction line is the chopper which allows switching the beam on and off in less than 200 µs.

In the CNAO treatment lines the chopper is made by four fast magnets powered in series according to a "+1, -1, -1, +1" scheme, creating a closed orbit bump to avoid an internal beam dump. In the path towards the XPR, the beam traverses only the first of the four magnets. In order to maintain the same functionality, the chopper bump towards the XPR is created with two correctors and the only chopper magnet involved, as shown in Fig. 6.

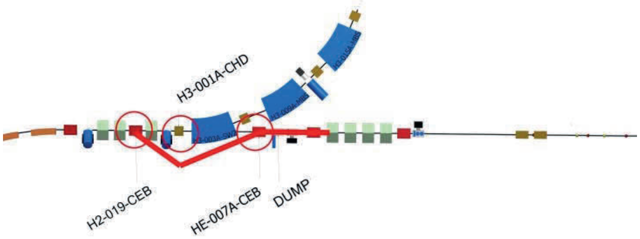

Figure 6: Chopper closure scheme and magnets involved.

When the beam has to be stopped, kicker H3-001A-CHD is switched off, while the other two magnets are powered on. In this way the beam is sturdily deviated from the nominal trajectory and intercepted by a dump. Access to the XPR, instead, is achieved by powering on all the three elements to create a beam bump that closes just before the dump, as shown in Fig. 7.

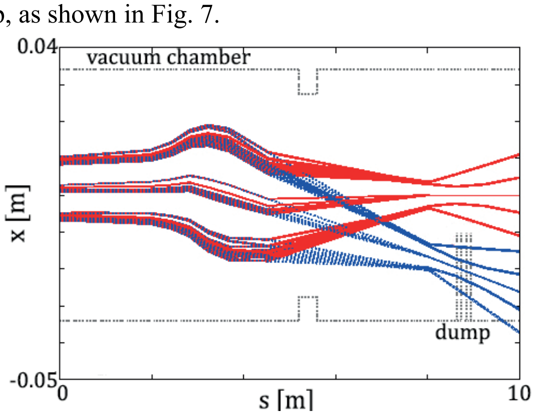

Figure 7: Beam sent to the experimental room (red) and to the dump (blue).

Optics is studied in such a way that, in correspondence of the dump, the beta functions are small enough (< 6 m) to let the beam avoid the dump when directed to the experimental room.

PRESENT STATUS

Installing a new beam line in a running facility is not an easy task because treatments cannot be suspended and a long stop would imply to ramp the number of patients down to zero, which requires approximately a few weeks, and then ramping the number of patients up again in a similar time.

The installation of the beamline and all the works that require access to the synchrotron hall or to stop the machine for any reason have been carried out as much as possible during the periodic maintenance periods (3 days 4 times a year) and during week-ends.

The beamline is presently installed. The first girder is be-ing equipped and pre-aligned in the synchrotron, see Fig. 8.

Figure 8: Status of installation of XPR optics line. Up left: XPR line in the synchrotron hall; up right: XPR room at actual state; down: scanning magnets positioned on the beam line (left) and moved out of the beam line (right).

COMMISSIONING STRATEGY

The starting point for the XPR commissioning is the beginning of May and it will last until the summer.

The program aims to bring all the energies for proton and carbon beams to nominal intensities and foci (i.e. those currently used in treatment rooms) for the four isocentres of the XPR. The isocenter with an irradiation field of 135×135 mm^2 (Fig. 2, panel D) will be commissioned first. The commissioning will start with protons at minimum energy (30 mm water equivalent). The chopper closure mechanism will be tested, in order to verify that no beam can go across the dump on the experimental line. If the chopper mechanism proves efficient, the line will be than commissioned for a set of energies along the proton energetic range. This procedure will be repeated for carbon beam with a similar set of energies.

After that, the settings for the intermediate energies will be deduced from a software minimization of the beam position along the line monitors. In the end, the threshold of the kicker H2-019-CEB will be set (it will be monitored by the safety system).

All the procedure described above will be repeated for the other isocenters.

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