

# COMMISSIONING OF HELIUM BEAMS AT CNAO

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## Abstract

CNAO (Centro Nazionale di Adroterapia Oncologica) is one of the few hadrontherapy centres all around the world that produce both proton and carbon ions beams.

It is based on a synchrotron in which the beams are extracted by a slow extraction mechanism by means of either a betatron core or an RFKO electrostatic exciter. Recently a third source, AISHa-CNAO (Advanced Ion Source for Hadrontherapy), has been installed to produce new species to be used for clinical or experimental purposes.

In this article, we show the commissioning status of the helium beams generated by the new source.

## INTRODUCTION

CNAO center has four beam lines for hadrontherapy treatments and one room (XPR-room) dedicated to experimental activities. Up to now the available species for treatments and experiments are proton and  $C^{6+}$  ions: a new low energy beam line [1] with a third source has been recently installed to produce new species with great impacts under the clinical, radiobiological and nuclear physics point of view. The installed source, named AISHa-CNAO, is an improved version of the source AISHa (Advanced Ion Source for Hadron therapy) designed by LNS-INFN [2, 3] to generate high brightness multiple-charged ion beams. After its installation, AISHa-CNAO has been commissioned and set for the production of Helium beams [4] that are particularly interesting for their clinical features. Helium beams are under commissioning in all the treatment rooms and in the experimental room: this paper shows the results and the status of this commissioning.

## LEBT COMMISSIONING

CNAO low energy line is shown in Fig. 1, where the part installed for the third source (O3-line) is highlighted by a red shape. The line has been designed considering the space left by the three sources and the original LEBT. The result was a line whose length makes beam transmission difficult considering the low beam energy (the magnetic rigidity is just  $0.02577 \text{ T}\cdot\text{m}$  due to LINAC design) and the number of installed diagnostics monitors. To overcome these difficulties, beam transport was studied dividing LEBT in three parts. Source settings and the magnets between the source and the spectrometer were optimized experimentally to produce the maximum current with the minimum emittance at the first diagnostics tank after the spectrometer. Right after, Twiss parameters obtained by the emittance measurement [4] were used as input for MADX [5] simulations: the two quadrupole triplets were matched to obtain the carbon ions Twiss parameters in the diagnostic tank (O2-023 tank) after carbon source spectrometer.

The Twiss parameters obtained by emittance measurement in O2-023 tank were used as input for MADX simulations to compute the right Twiss parameters at the LINAC entrance. The dispersion was found by measuring the horizontal displacement of the beam changing the extraction high voltage of the source.

MADX simulations were just the starting point: optimizations were done changing simultaneously the currents of the quadrupoles of each triplet. The result was a transmission of about 60% along the O3-line and of 90% from the end of O3-line to the LINAC entrance where, at present, about  $500 \mu\text{A}$  can be transported. To improve this scenario the installation of two diagnostic tanks is foreseen in the two-year period 2026-2027.

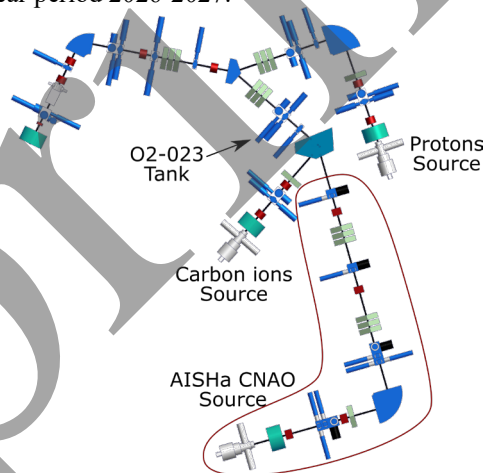


Figure 1: LEBT layout with AISHa-CNAO source. O3-line is high-lighted by a red shape.

## LINAC AND MEBT COMMISSIONING

Next step was to accelerate the helium beams to the energy of  $7 \text{ MeV/u}$  through a LINAC, which at CNAO includes a RFQ (RadioFrequency Quadrupole) cavity and an IH-DTL (Interdigital H-type Drift Tube Linac). The 48 accelerating cells of the last one are divided in four sections among which 5 sections with pulsed magnets (13 quadrupoles and 4 kickers) are present.

Pulsed quadrupole currents have been scaled by the ones used for protons using the magnetic rigidity.

Considering that the power of a cavity is proportional to the square of the accelerating voltage and that the energy gain is proportional both to the voltage and to the ratio between atomic and mass number, the power of the amplifiers for Helium ( ${}^4\text{He}^{2+}$ ) was obtained multiplying by  $4/9$  the power used to accelerate protons ( $H_3^+$ ).

After a final tuning of these values, an acceleration from  $8 \text{ keV/u}$  to  $7.148 \text{ MeV/u}$  has been obtained, as given by a TOF (Time Of Flight) measurement, with a transmission through the LINAC of about 28%, that is similar to LINAC

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proton and carbon ions transmissions. CNAO MEBT layout is shown in Fig. 2.

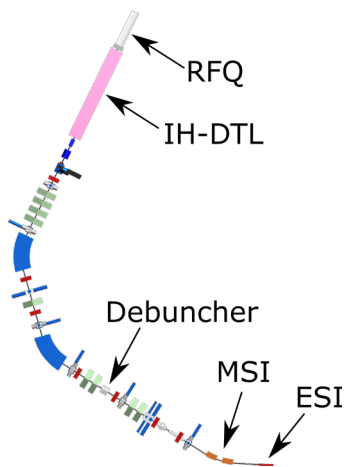


Figure 2: LINAC and MEBT layout at CNAO.

Besides quadrupoles, correctors and two dipoles, an RF cavity (*Debuncher*) is installed to shape beam momentum spread for injection. Debuncher setpoint has been obtained with the same criterion used for RFQ and IH; quadrupoles and dipoles have been obtained optimizing protons optics while kickers have been adjusted to center the beam along the line.

MEBT transmission is around 85%, with a current of about 100  $\mu\text{A}$  as measured by the last Faraday cup of the beamline.

## INJECTION AND ACCELERATION

Injection in the synchrotron (see Fig. 3) is realized by a multi-turn injection mechanism: an electrostatic (ESI) and a magnetic septum (MSI) inject the beam from MEBT into the ring where two magnets along the ring (named injection bumpers) create a horizontal bump that decreases while the beam pulse is injected. Synchrotron optics is set to make beam circulating with a negative average momentum spread.

Measuring the response matrix of the first dipole in the MEBT with carbon and helium ions it was possible to have a precise ratio between the magnetic rigidity of the two particles. This ratio was used to obtain the current of all the synchrotron magnets for helium injection starting from the currents of carbon beams. A scan in the transverse phase spaces,  $x-x'$  and  $y-y'$ , with the two final horizontal and vertical MEBT correctors matched synchrotron closed orbit to obtain about  $7.2 \cdot 10^9$  injected particles.

After injection optimization, RF cavity was switched on to trap the coasting beam in the RF bucket. Since the pickup installed in the synchrotron are sensible just to a bunched beam, a measurement of the amplitude of a pickup signal as a function of RF frequency allowed to find the right trapping frequency. This result was very close to the theoretical value computed with the following relation:

$$F_{RF} = F(B) \cdot \left(1 + x \cdot \frac{\eta}{D}\right)$$

where  $D$  is the dispersion,  $\eta$  is the slippage factor,  $F(B)$  is the synchronous particle revolution frequency,  $B$  is the

dipole magnetic field and  $x$  is the injection position at a maximum dispersive position that maximize the transverse acceptance of the ring.

Synchrotron dipoles permit to accelerate Helium up to 320 MeV/u. Only the energies corresponding to a penetration in water between 30 mm and 320 mm are interesting under a clinical point of view and have been commissioned up to now. Higher energies will be interesting for nuclear physics experiments and will be commissioned later. The relationship between the energy in MeV and the penetration in water was firstly found by FLUKA simulations obtaining 62.3 MeV/u for 30 mm and 227.05 MeV/u for 320 mm. Comparing the magnetic rigidity of clinical Helium beams with proton and carbon ions the minimum Helium energy has the same rigidity of the highest proton energy, while the highest Helium energy overlap carbon ions rigidity up to 104 mm carbon ions rigidity: for this reason, as initial guess, all the quadrupoles, sextupoles and kickers strengths for each acceleration energy have been put equal to 104 mm carbon ions strengths.

Acceleration is performed at CNAO by the use of a B-train, calibrated cycle by cycle by the RF-master method [6]. Helium was first accelerated without B-train just to investigate the synchrotron magnet ramps and the effectiveness of RF phase and radial loop. After having reached the maximum energy, B-train parameters were adjusted to make properly work its four main functionalities: feedback on dipole current, B-train reset after injection using beam orbit, adjustment of magnetic field at extraction comparing the revolution frequency to a reference frequency, compensation of B-train electronics drift [6].

Once B-train was properly working, an acceleration efficiency of about 60% has been reached with  $4 \cdot 10^9$  Helium ions accelerated.

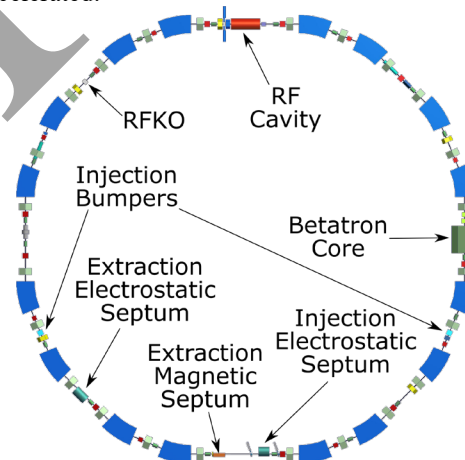


Figure 3: CNAO synchrotron layout.

## EXTRACTION AND HEBT COMMISSIONING

Beam can be slowly extracted at CNAO feeding the third order resonance by a betatron core [7] or by RFKO [8, 9]. Since nowadays clinical beams are extracted only by

RFKO while betatron extraction is used just in the experimental room, Helium has been commissioned up to now only using RFKO extraction.

CNAO RFKO works applying an RF voltage with both AM and FM modulations. The RFKO maximum frequency is about 1/3 of revolution frequency but it is finely adjusted for each energy. Amplitude ramp has a theoretical shape to have a quite uniform intensity but it is regulated in real time by a feedback ("voltage feedback") on the particles measured by the dose delivery system. The particles measured by the dose delivery system are also used for a feedback ("air-core feedback") on the current of an air-core quadrupole to smooth intensity profile on a 10 kHz scale. First, Helium extractions were studied without voltage and air-core feedback in order to find the best synchrotron settings that maximize extracted particles as measured at the beginning of HEBT line (see Fig. 4). The setting obtained using the 104 mm carbon ions settings worked well at Helium highest energies while extraction efficiency was too small at the lowest energies.

To increase extraction efficiency for 30 mm Helium the following strategy has been followed:

- At the operating tune ( $Q_0$ ) a scan has been done on the frequency  $F_{\max}$  to find the value  $F_{\max}(Q_0)$  that maximizes efficiency.
- It has been changed the "geometry of extraction", defined by  $(X_{\text{ESE}}, X'_{\text{ESE}}, \langle \Delta p/p \rangle)$ , where  $X_{\text{ESE}}$  is the distance between circulating beam and electrostatic septum,  $X'_{\text{ESE}}$  is the divergence of the circulating beam with respect to the electrostatic septum,  $\langle \Delta p/p \rangle$  is the average momentum spread at extraction.
- For each set  $(X_{\text{ESE}}, X'_{\text{ESE}}, \langle \Delta p/p \rangle)$  the revolution frequency has been measured in order to change the reference frequency.
- A scan has been done on the horizontal tune changing at the same time  $F_{\max}$  according to the formula  $F_{\max}(dQ) = F_{\max}(Q_0) - dQ \cdot f_{\text{rev}}$ , where  $dQ$  is the difference in horizontal tune from the operating value  $Q_0$  and  $f_{\text{rev}}$  is the revolution frequency.

The most efficient set  $(X_{\text{ESE}}, X'_{\text{ESE}}, \langle \Delta p/p \rangle)$  for 30 mm Helium has been applied to all the energies and the best tune has been searched for each energy.

The magnetic and electrostatic septa were first scaled from 104 mm carbon ions values respectively using magnetic rigidity and magnetic rigidity times the relativistic beta factor, but then they were finely adjusted to set beam position at the first two monitors in the HEBT equal for all the energies: in this way scaling all the HEBT magnets with the magnetic rigidity allowed to transport all the energies up to the isocenter of one of the treatment rooms (line Z). A fine steering centered within 3 mm along all the line guaranteed a perfectly centered beam at the isocenter with zero divergence in both transverse planes. Once beam was transported to the isocenter, voltage and air-core feedbacks were switched on: the parameters used for proton beams worked well while the proportional term of the air-core feedback has been scaled according to the ratio  $N_p/\text{counts}$  of each Helium energy and  $N_p/\text{counts}$  of 30 mm proton beams, where  $N_p$  is the number of particles that hit the dose

delivery system and  $\text{counts}$  is the dose delivery digital counts due to the  $N_p$  particles.

As for the other particles, four intensities have been commissioned. Considering the properties of the Bethe-Bloch equation for the stopping power of particles traversing matter, for each penetration depth, the energy per nucleon of proton and Helium is quite the same and the dose released by Helium is a quarter than proton dose. As a consequence Helium commissioned intensities were a quarter than proton intensities: the maximum intensity was  $1 \cdot 10^9$  helium ions/s and the other three intensities were 50%, 20% and 10% than the maximum one.

After the commissioning of all energies at the isocenter, measurements have been performed with a water Bragg peak detector. Since differences up to 1 mm were found, all the synchrotron and HEBT settings have been rescaled in order to obtain a discrepancy within 0.1 mm. Beam sizes are under optimization in line Z in order to have that Helium sizes are between proton and carbon ions ones in all energy range.

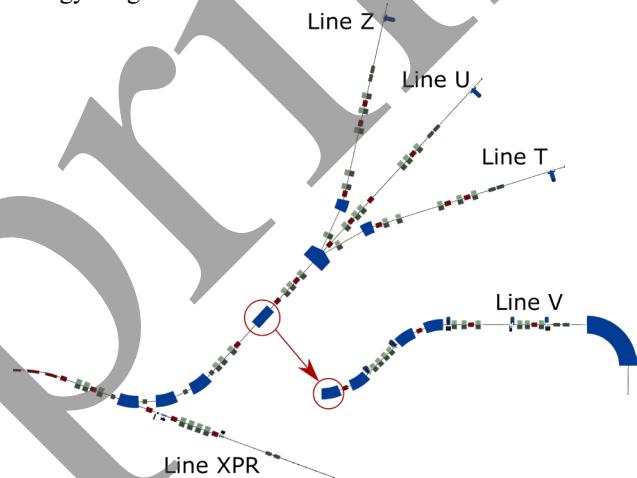


Figure 4: HEBT layout at CNAO showing all treatment lines (named Z, U, T and V) and experimental room (XPR) line.

## CONCLUSION

The Helium produced by the source AISHa-CNAO has been transported along all the sectors of CNAO machine from the new dedicated LEBT up to one of the treatment rooms. Optimizations are ongoing to shape beam at the isocenter according to medical physicists' requests. Helium beams will be used for in vitro and in vivo experiments to qualify and prove its radiobiological effects before clinical trials.  $\text{He}^{2+}$  will become a new ionic species that CNAO will use for patient treatments in addition to proton and carbon ions. Helium commissioning will go on in the next months for beam qualification in the other treatment rooms and in the CNAO experimental room.

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