STATUS REPORT OF THE CNAO CONSTRUCTION AND COMMISSIONING

M. Pullia, CNAO, Pavia, Italy
on behalf of the CNAO collaboration.

Abstract

The CNAO (*National Center for Oncological Hadrontherapy*) is the first Italian center for deep hadrontherapy. The main accelerator is a synchrotron, based on the PIMMS design, capable to accelerate carbon ions up to 400 MeV/u and protons up to 250 MeV. Four treatment lines, in three treatment rooms, are foreseen in a first stage. The CNAO facility, has been designed for a completely active beam delivery system, in which a pencil beam is scanned transversely and the extracted beam energy can be changed on a spill to spill basis. The commissioning of the synchrotron started in August 2010. At the beginning of 2011 the first Spread Out Bragg Peaks with proton beams in the energy range 120-170 MeV/u, matching the first foreseen treatments, have been measured.

The commissioning of the machine with protons has now been completed and authorisation to treatment of patients has been obtained from the competent authorities[1]. The commissioning with carbon ions is in progress.

CNAO HISTORY

The origin of CNAO dates back to 1991, when the realisation of a dedicated facility for hadrontherapy in Italy was first proposed [2]. In the same year the ATER experiment was launched by INFN.

In 1996 CERN, Med-Austron and TERA started the Proton Ion Medical Machine Study (PIMMS) [3] in collaboration with GSI. Onkologie-2000 joined later the study group. The study lasted approximately four years and resulted in a green-field conceptual design, with a particular attention to the theoretical aspects, which has been used by TERA as the basis for the CNAO design.

In the year 2001, the Ministry of Health created a non-profit organization, named CNAO Foundation, to build and subsequently run the National Center for Hadrontherapy. In 2003 CNAO acquired the final design and the design group from TERA and in 2005 the construction actually started.

The construction phase ended in February 2010 and the second phase, the so called clinical trials, was then started and will bring to the treatment of some hundreds patients in the period 2010-2012.

CNAO ACCELERATOR OVERVIEW

The CNAO has been designed to perform treatment of deep seated tumours with beams of ions up to Carbon (eventually Oxygen, but with a reduced range). Dose rate up to 2Gy in 2l in 2-3 min and range up to 27 g/cm^2 are foreseen. The main design parameters are summarised in Table 1.

Table 1: Main Design Parameters of CNAO

Particle species	p, He^{2+}, C^{6+} (O^{8+})
Beam range	from 3 g/cm^2 to 27 g/cm^2
Range adjustment	0.1 g/cm^2
Beam size	4 to 10 mm FWHM
Beam size step	1 mm
Field size	20×20 cm^2
Dose uniformity	±2.5%
Dose rate	2Gy in 2l in 2-3 min

The CNAO accelerator system, shown in Figure 1, includes two ECR sources, each with a dedicated spectrometer, a common RFQ and LINAC system, a synchrotron of about 25m diameter and four extraction lines transporting the beam to three treatment rooms.

The whole injector, including sources and LINAC, is very compact and has been placed inside the synchrotron ring.

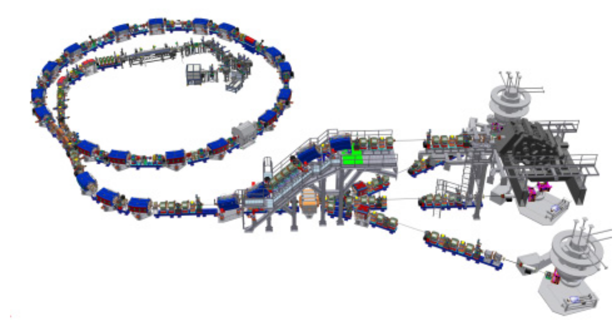

Figure 1: Layout of the CNAO accelerator and lines.

The treatment rooms are served by horizontal beam lines, but in the central room an additional vertical beam is also available. All the lines are equipped with a pair of scanning magnets which allow delivering the dose to the tumour by scanning over an area of 200 mm x 200 mm.

The CNAO accelerator allows pulse to pulse energy variation for a completely active 3D beam scanning.

CNAO COMMISSIONING

The commissioning of the CNAO accelerator has been carried out, in the construction phase, alternatively with the construction of the building and of the accelerator itself. The commissioning up to the first turn of the synchrotron has already been reported [4] and details on the commissioning of the synchrotron are given elsewhere in this conference [5].

After the successful commissioning of the injector with both protons and carbon ions, it has been decided to concentrate all the effort on the commissioning with protons. The aim was to put all the systems into operation to start treatments with protons as soon as possible, according to the authorisation programme approved by the Italian Health Authorities.

Table 2 summarizes the main milestones of the CNAO commissioning.

Table 2: Milestones of the CNAO Commissioning

Jan 2009	LEBT with H_3^+ and C^{4+} beams
Mar 2009	RFQ with H_3^+ and C^{4+} beams
Sep 2009	LINAC with H_3^+ and C^{4+} beams
Dec 2009	First turn in synchrotron
Jan-Jul 2010	Completion of installation
Aug – Dec 2010	Synchrotron with proton beams
Jan – May 2011	Proton beam characterization in treatment rooms
Jun – Jul 2011	Radiological cells irradiation
Aug 2011	Synchrotron and HEBT with Carbon ions

Slow Extraction

Slow extraction is the most critical part in the beam production. The beam in the treatment room must be as constant as possible both in time and in transverse characteristics. Slow extraction at CNAO is performed with the so called "amplitude-momentum selection" scheme. With this method, a beam large in momentum with respect to the stop-band is pushed, in tune, against the resonance with a betatron core.

To help reducing the ripple on the extracted beam, additional countermeasures have been foreseen, that is the use of the empty bucket technique [6] and of an air core quadrupole [7]. Without any countermeasure, the spill is strongly modulated (maximum/average beam intensity = 55) especially because of the large 100 Hz ripple of the dipole field. The efficacy of the ripple control techniques is summarised in Table 3 and in Figure 2.

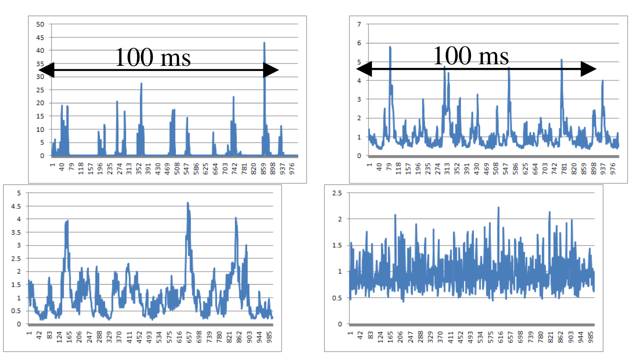

Figure 2: Ripple compensation (10 kHz measurements). On the left, without compensation (above) and with empty bucket (below). On the right, without air core quad (above) and with (below).

Table 3: Ripple Control Efficacy

	I_{max}/I_{ave}
No empty bucket, no air core quad	55
With empty bucket channelling	7
With empty bucket and air core quad	3

The beam extracted from the synchrotron has an asymmetric distribution because of the extraction process.

In the vertical phase space, the beam has approximately the same distribution as the circulating beam; in the horizontal phase space, on the contrary, the beam is distributed along the extraction separatrix and has a trapezoidal profile (consistent with the "bar of charge" distribution), as shown in Figure 3.

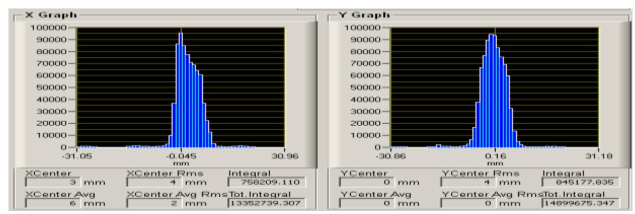

Figure 3: The slowly extracted beam at the beginning of the CNAO extraction line.

As mentioned in the previous section, the beam size and position stabilities are important for the quality of treatment. As an example, Figure 4 shows the beam position measured at the end of the extraction line for different energies. The results obtained at CNAO are summarised in Table 4.

Table 4: Beam repeatability at CNAO

Beam position repeatability (same energy)	0.2 mm
Beam position precision (at different energies)	0.5 mm
Beam size repeatability (same energy)	0.5 mm

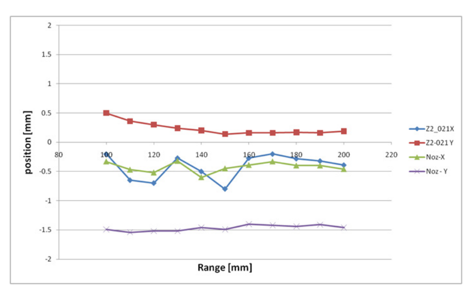

Figure 4: Beam position vs range measured in the last two monitors in the HEBT.

During the irradiation of a iso-energy slice of a tumour, the beam is generally extracted continuously, without interruptions. Nevertheless, at the end of a slice or even during a slice in case of a large displacement between two consecutive voxels, it is necessary to be able to stop the beam quickly. This task is accomplished in the extraction line with four fast magnets powered in series according to a (+1, -1, -1, +1) scheme, called "HEBT Chopper", illustrated in Figure 5. Two monitors just before the beam dump, allow to verify the beam quality before sending it to the treatment room.

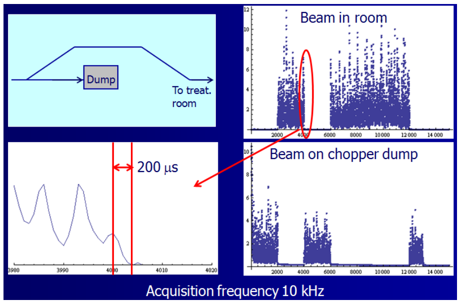

Figure 5: The HEBT chopper stops (and starts) the beam within 200 μs from trigger.

Besides the HEBT chopper, CNAO features also a faster abort system that dumps the circulating on an internal dump in less than 50 μs.

Beam Scanning

Once the beam reaches the treatment room, it is measured in the nozzle and scanned with two fast magnets placed approximately 6 m upstream the iso-center. The scanning is "dose driven", that is the beam is kept on the voxel until the prescribed dose is reached and then it is moved to the next voxel. Two set of monitors are used in the nozzle for redundancy reasons.

Quantitative results have been obtained irradiating homogeneous rectangles and parallelepipeds. The resulting dose profiles have errors to within ±2.5%, that is conform to specifications. Figure 6 Shows a Spread Out Bragg Peak measured on a radiochromic film (the film was lying on the median horizontal plane of a parallelepided).

The beams produced have been characterised to be used with the treatment planning system. Simulations with Monte Carlo codes have been performed to find a model usable in the TPS. Both transverse and longitudinal measurements have been made. The longitudinal depth-dose profiles have been measured with a PeakFinder and the transverse ones with a PinPoint ionization chamber moved inside the phantom.

The matching between measurements and simulation is better than 0.1 mm.

Using the SOBP, measurements of cell survival vs dose have been performed. The results were positive and useful to obtain the final permission to treat patients.

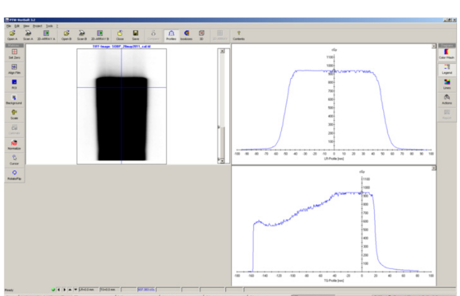

Figure 6: SOBP measured on a radiochromic film.

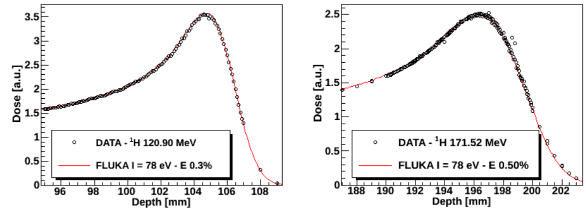

Figure 7: The match between simulated energy and the measured one is better than 0.1 mm in range.

The cells were irradiated inside a water phantom, the setup is shown in Figure 8, at three different positions inside the SOBP at 8 different dose levels.

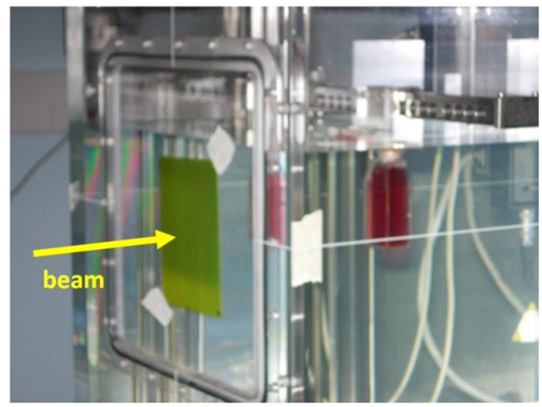

Figure 8: Experimental setup for cells irradiation. The flask (the bottle with red liquid inside in the picture) is placed inside water and a film is placed at the entrance of the phantom.

CONCLUSIONS

The commissioning of the technical part of the CNAO system for hadrontherapy is complete for the proton part and is in progress for the carbon ion part. The permission to start with the patient treatments has been obtained and the medical activities are about to start.

REFERENCES

[1] S. Rossi, Eur. Phys. J. Plus (2011) 126: 78
[2] U. Amaldi and G. Tosi, *Per un centro di teleterapia con adroni*, TERA 91/1 GEN 1 (1991).
[3] L. Badano, M. Benedikt, P. Bryant, M. Crescenti, P. Holy, A. Maier, M. Pullia, S. Rossi, *Proton-Ion Medical Machine Study (PIMMS)*, Part I and II, CERN/PS 1999-010 DI and CERN/PS 2000-007 DR, Geneva (2000).
[4] G. Bazzano, IPAC 2010, MOPEB005
[5] C. Priano et al, IPAC 2011, WEPS007
[6] R. Cappi and C. Steinbach, PAC 1981
[7] D. Manglunki et al, PS/OP/Note97-30(MD)