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ORIGINAL PAPER

The CNAO facility: operation and maintenance

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Abstract

Purpose CNAO is one of the few centres in the world that can treat patients with both proton and carbon ion beams and, in the next few years, with Boron Neutron Capture Therapy. The CNAO Synchrotron is not a commercially available machine but was designed by CNAO and built to specification by hundreds of different firms. This paper gives a brief overview about the operation and maintenance of the CNAO facility together with an anticipation of the technologies that are going to be installed in the near future and the more significant upgrades that are on the way.

Methods CNAO adopted a hybrid method for maintenance, partly performed internally (for the accelerator) and partly by service companies (for the plants), obtaining a high reliability and the quickest response to technical problems that may delay treatments.

Results With just under 5000 treated patients and a system reliability of 98.7%, CNAO's approach is effective in guaranteeing the necessary continuity in patient's treatments.

Conclusions CNAO is growing with the addition of two new accelerators, expanding its treatment possibilities.

Keywords Hadrontherapy · Medical particle accelerator operation · Medical particle accelerator maintenance

1 Introduction

CNAO, the Italian National Center for Oncological Hadrontherapy ("Centro Nazionale di Adroterapia Oncologica" in Italian) is located in Pavia, approx. 30 km south of Milan, and is one the few facilities in the world that is capable of treating tumours with both protons and carbon ions [1]. The Foundation that manages it was created in 2001 with the aim of building a synchrotron that was an evolution of the one defined during the Proton Ion Medical Machine Study (PIMMS) at Conseil Européen pour la Recherche Nucléaire (CERN) [2]. The design of both the machine and the building were finalized between 2002 and 2004 while construction works began in 2005 and were completed in 2009.

The CNAO synchrotron is a prototype, built to the specifications that were prepared by CNAO physicists, engineers and technicians together with colleagues from CERN and Istituto Nazionale di Fisica Nucleare (INFN): more than 500 companies have participated to the construction of the various components of the machine and of the plants that are required to operate it. For this reason, both the operation and the maintenance of the entire facility require an approach that is somewhat different from that of a typical industrial plant.

CNAO was officially launched on February 15th, 2010; from that moment on, a phase of clinical validation started, which lasted around three years. The first patient was treated in September 2011; since then, almost 5000 patients have been treated at CNAO.

2 The CNAO facility

The CNAO facility stands in an area of about 37,000 square meters and is composed of a main building, the synchrotron hall, a power converter room, a front and a back yard and a dedicated electrical sub-station (see Fig. 1).

The main building develops on four floors, one of which is underground, and houses all the offices of the CNAO personnel, the patients' reception and waiting room plus the medical imaging area, equipped with a Magnetic Resonance (MR) and a Computed Tomography (CT) scanner (soon to

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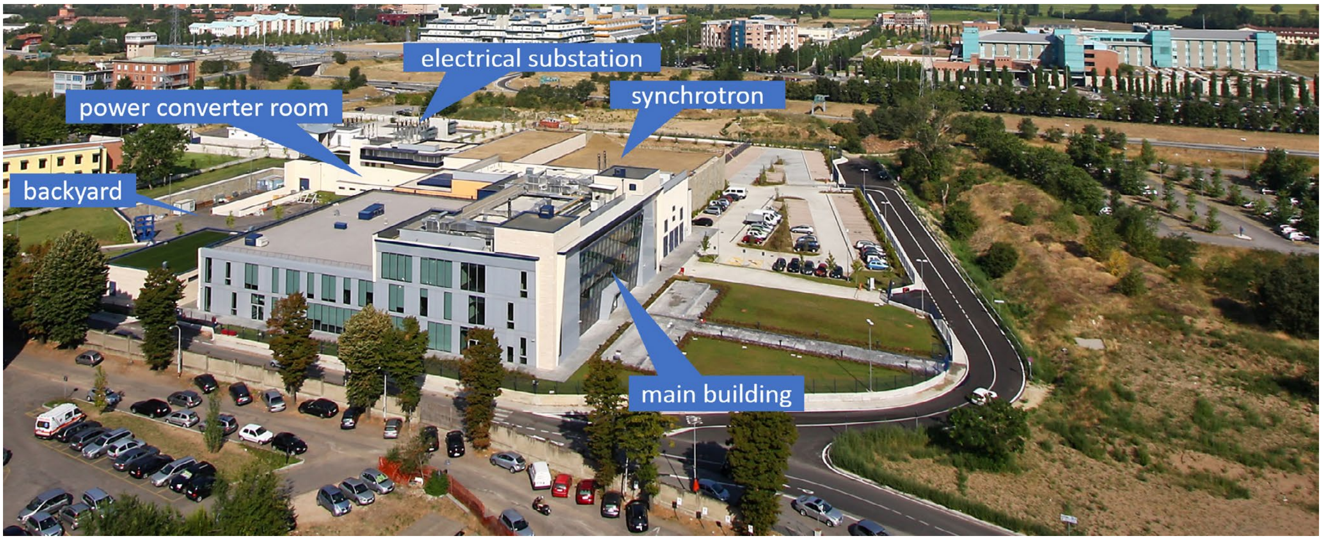

Fig. 1 Aerial view of the CNAO facility

be expanded with a second CT scanner and ready for receiving a second MR scanner too).

Next to the main building is located the bunker where the synchrotron is installed together with the mechanical plants necessary for the accelerator and the main building.

In order to save area, the synchrotron is a compact design in which the "injector" is inside the ring itself (see Fig. 2). The injector is the part of the machine that extends from the ion sources (where the particles are produced) through the Linear Accelerator (LINAC, where they are pre-accelerated) up to the point where the ions are injected into the ring.

When accelerated to the required energy, the particles are extracted and transported to the three treatment rooms by means of an extraction line that splits in four. There are four lines because while all the three treatment rooms receive a horizontal beam, the central one also receives a vertical beam for an increased flexibility in choosing the beam delivery angle to the patient. As per today, CNAO does not have a gantry (i.e. a rotating extraction line that allows delivering the beam from any angle) but is participating in the HITRIplus project [3], which also involves CERN, INFN and MedAustron, that aims at designing a compact gantry for carbon ions, to be installed in the future [4, 5].

All three rooms are equipped with a fully automated, six degrees of freedom robotic couch, together with an in room imaging system, for precise patient positioning.

For improved accuracy, the beam delivery uses the active raster scan technique, driven by a Dose Delivery system that precisely counts how many particles reach which position of the tumour. CNAO is already capable of treating moving targets by means of respiratory gating, but will move in the near future to a more advanced "4D" approach. This means that instead of waiting for the tumour to be in a target position, multiple treatment plans will be prepared, for the various breathing phases, which will be delivered following the patient's breathing, position per position.

Figure 2 shows two particle sources, one for protons and the other for carbon ions. A third source has already been installed and is waiting for the final authorization by the Authorities to be switched on (see Fig. 3). This additional source is capable of producing further species, like Helium and Oxygen – which are the next "big thing" in the hadrontherapy world [6] – and Iron ions. These will not be used for curing cancer, but for research purposes. In fact, as it can be seen in Fig. 2, CNAO has an additional beam line that feeds the so called Experimental Room where various researchers from a number of institutions come to irradiate a variety of experiments.

Finally, the power converter room contains all the power converters (around 225) that drive the synchrotron magnets, feeding a very precise current to each of them. The power converters, the supporting plants, the electronic devices and the computing power that control the accelerator all require electricity to operate: this power comes from a dedicated electrical sub-station connected to the 132 kV Italian high voltage grid.

With so many electrical loads, one can expect a significant energy consumption. In fact, the entire facility consumes, on average, 11.5 GWh of energy per year. It is worth mentioning that only 30% of the total consumption is due to the synchrotron accelerating particles: the majority of the consumption comes from the support plants, the building and, to a lesser extent, from the part of the accelerator that works constantly, even when there is no beam delivered to the treatment rooms. Among these are the ion sources and their dedicated beam lines and the LINAC, which is constantly pulsed to keep its temperature stable.

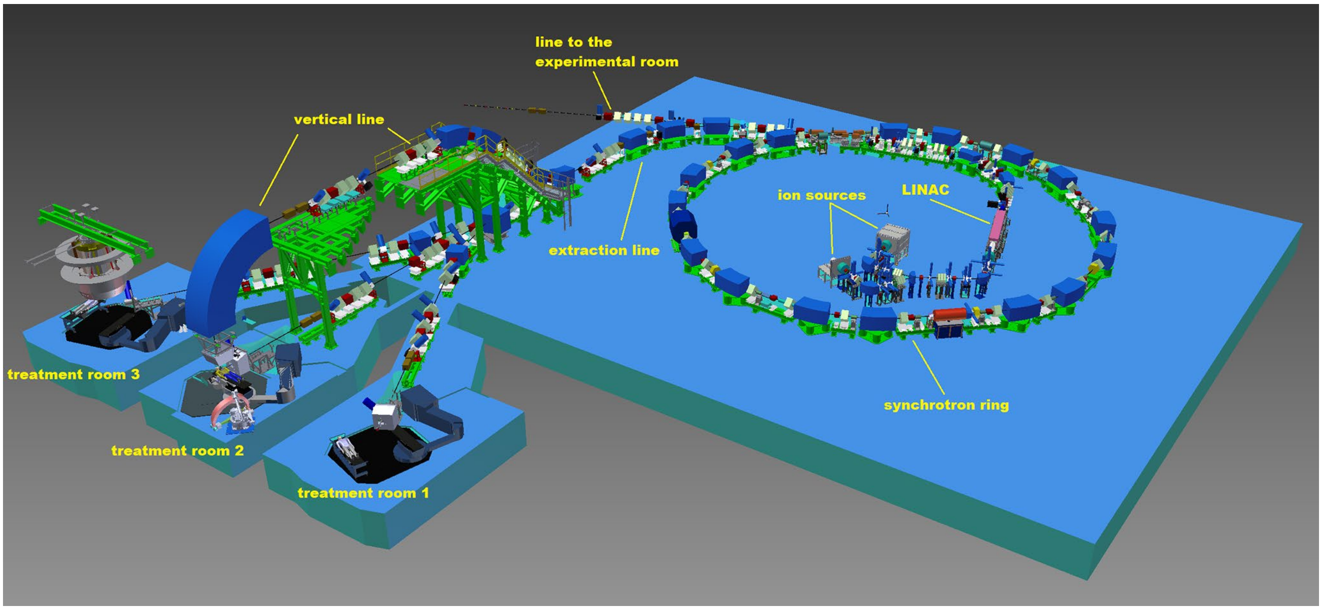

Fig. 2 Layout of the CNAO synchrotron

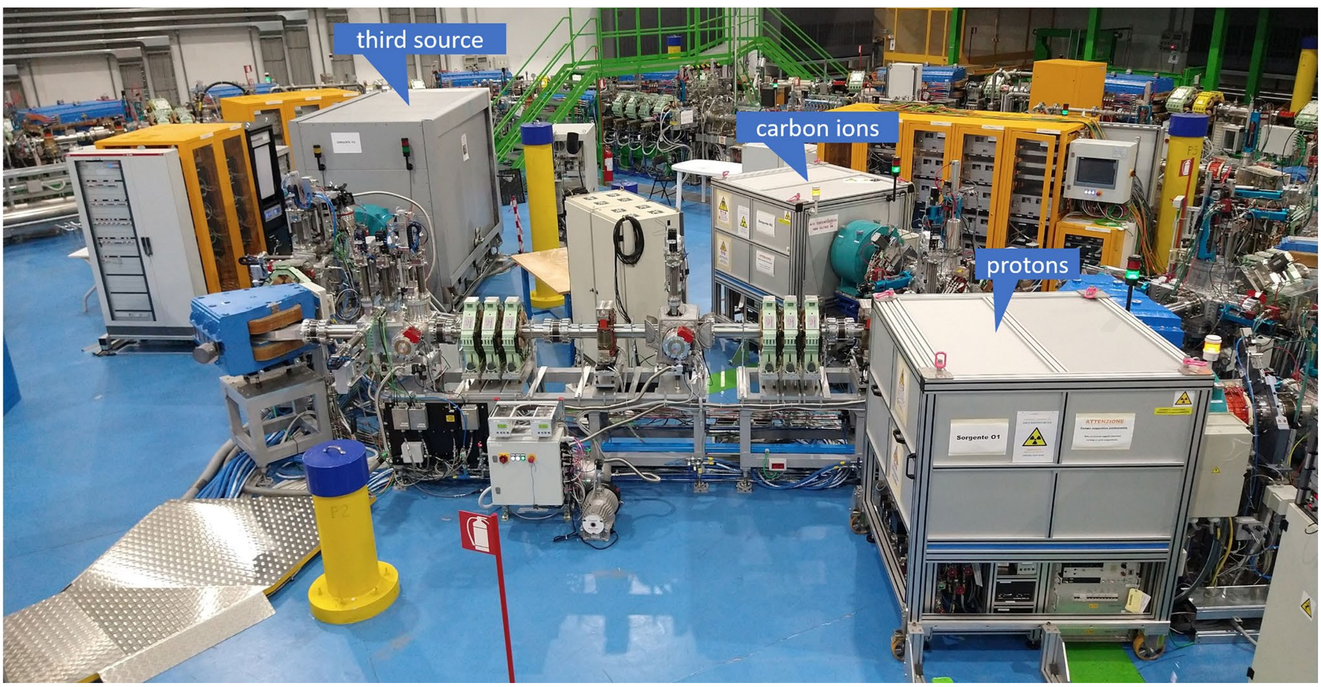

Fig. 3 Detail of the ion source area, showing the third source in place

3 Operation of the CNAO facility

For technical reasons, the synchrotron is "ON" 24 h a day, 7 days a week: in fact, the procedure for switching it on – and running the calibration tasks that are needed after a full shutdown – takes about one day and a half.

Being ON does not mean that it is accelerating particles constantly, but that it is ready to accelerate at any given moment: the operation statistics that have been gathered since 2011 show that it actually accelerates a beam for about 25% of the day. The accelerator is then manned around the clock by technicians that reside in the Main Control Room and constantly monitor all the systems. These technicians, called Operators, work on three shifts: the morning shift, from 6 a.m. to 2 pm; the afternoon shift, from 2 p.m. to 10 p.m.; the night shift, from 10 p.m. to 6 a.m. of the next day (see Fig. 4). During weekdays, especially in the morning and afternoon when the treatments are delivered, two operators are simultaneously on shift. This choice was made to improve the responsiveness in case of problems: not only two skilled people can react faster, but also they can cooperate when an intervention on multiple systems is needed. Furthermore, the operators do not work exclusively on shifts: all of them have a “secondary task”, related to the maintenance of the various sub-systems that make up the accelerator. On average, they spend one week per month in their office and three in the Control Room. The side effect of this situation is that the operators are system experts themselves and, if something happens to that system during their shift, they can intervene autonomously without waiting for someone to come. Over the years, this proved to be an effective approach, which give advantages in terms of machine reliability and helps attenuating the repetitiveness of the work in the Control Room.

As Fig. 4 shows, superimposed to the operator’s shifts are the other activities carried out at CNAO. In particular, treatments are executed five days a week, from 7:30 a.m. to approx. 9:30 p.m. The end time is not fixed: it depends on various factors, such as the number of patients per day (typically 40 to 50), their treatment plan complexity, delays that can occur for both clinical and technical reasons.

Before treatment start, a number of Quality Assurance (QA) measurements are performed to check the quality of the beam and certify it is suitable for treating human beings.

The hours between the end of the treatments and the start of the QA, which approximately correspond to the night shift, are available for various activities: they can be used for routine measurements needed to monitor the health state of the accelerator; for using the experimental room; for “lightweight” test sessions of upgrades and maintenances. Lightweight here means that since the clinical activity in restarting in a few hours, to reduce the risk that an accident delays the patients only those tests and maintenances that are less invasive can be scheduled. Given the variety of activities during the night, in this case the second operator is replaced by a machine expert who, typically, is the one in charge of the tests or of the maintenance.

Nevertheless, the tendency is to always have two operators on shift with the addition of other personnel that is required for the night activities. This requires increasing the number of operators from the actual nine to twelve: CNAO will work on this the next few years.

Since there are no patients, during weekends the regime is slightly different. In particular, one shift is systematically devoted to the measurements of the medical physicists, who perform periodical checks and, mainly, verify the treatment plans of patients that are about to start the next Monday. The other two shifts are used for more impactful tests and maintenances and for putting upgrades into service.

Indeed, upgrades are a very important part of the life of CNAO synchrotron. As technology evolves, three aspects should be considered:

1. performance of the systems can be improved, sometimes significantly;
2. since electronics is a fundamental building block of the accelerator and it rapidly evolves, sometimes a component is discontinued and some replacement has to be found;
3. software – another key building block – becomes obsolete very soon and needs to be replaced to maintain compatibility with modern hardware.

In other cases, the driving factor for upgrades is to equip the accelerator with some new features that were not foreseen in the beginning but would be beneficial to have currently.

For one reason or another, such a machine is constantly under development and it is very important to have periods available for testing and putting upgrades into service.

4 Maintenance of the CNAO facility

The maintenance routine of the CNAO facility aims at achieving two apparently contradictory objectives: having a high reliability of the entire system – which implies devoting a significant time to maintenance – and, at the same time, subtract to the clinical routine a time as low as possible.

To maintain a high quality of the therapy, the patients’ sessions should not be interrupted for more than five days in a row and no patient should suffer more than one of these interruption during his/her treatment period [7, 8].

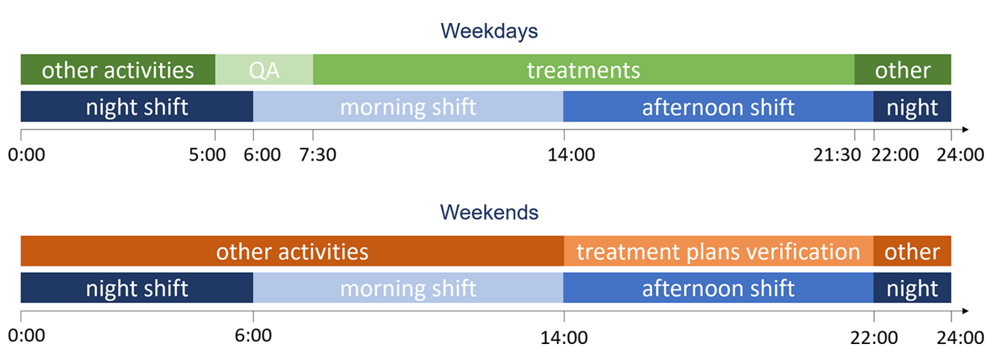

Fig. 4 Distribution of the activities during the days

This means that maintenance should be distributed on the calendar in a very accurate way. The experience accumulated in all these years gave rise to the following routine:

- three stops per year are devoted to maintenance of the accelerator and the mechanical plants;
- one stop per year is devoted to the IT infrastructure;
- one stop every 18 months is devoted to the high voltage electrical substation and to the medium and low voltage switchgear.

Each stop, regardless of the topic, lasts five days. The accelerator is put in a standby state (there are various degree of standby states, depending on the maintenance that is going to be performed) the evening before the first day, just after the treatments end. Maintenance runs for three days and a half; the accelerator is restarted in the afternoon of the fourth day. The fifth day is used to check the systems and recalibrate the beams.

The stops are organized at least one month apart of each other, precisely to guarantee that a single patient does not have to undergo more than one and far from those periods, like summer or the end of the year, when people are on holidays or interruptions are already present in the calendar.

These stops are not enough to do the maintenance of large systems, for instance the 225 power converters previously mentioned. In this case, short sessions are organized during weekends and night shifts, often exploiting the fact that the operators, because of their secondary task, are also trained to carry out maintenance.

This sentence already unveils a fundamental element of the maintenance strategy at CNAO: all the maintenance of the accelerator and its components is done internally.

Table 1 Number of sessions lost for technical reasons divided per system and year; the last row shows the total number of sessions programmed during the corresponding year

	Year				
	2019	2020	2021	2022	2023
Accelerator	9	3	3	9	6
Beam Diagnostics	0	0	3	12	2
BTrain	0	0	0	2	1
Control System	8	2	7	5	11
Dose Delivery System	1	1	1	1	13
LINAC	39	34	22	61	16
Patient Safety System	4	11	4	4	11
Power Supplies	38	36	21	57	29
Radio Frequency Cavity	9	9	4	1	8
Particle Sources	2	0	2	1	2
Timing System	3	8	4	4	3
Vacuum System	5	2	1	3	2
Lost sessions	**118**	**106**	**72**	**160**	**104**
Number of sessons	**10,604**	**10,410**	**10,353**	**10,699**	**9,925**

As mentioned before, this accelerator has been designed by CNAO physicists, engineers and technicians who looked after the construction of the various components, participated to their installation and start-up phase and took care of them all these years as well. The vast majority of those people are still part of CNAO and deal with maintenance, both preventive and service.

Even if, in this way, they a bigger responsibility is placed on their shoulders, there is the advantage that they are the greatest experts of this accelerator, both for their own subsystem and transversally. Furthermore, being present at CNAO every day, they can closely follow the evolution of each unwanted behaviour much closer than someone could from an external company. Finally, during office hours their presence guarantees the promptest response to any failure it may occur, once again in a faster way with respect to a service company and for a much lower cost.

Even outside office hours, most of them are available to be contacted to offer support in case of technical problems, both guiding the operators in the simpler actions and, in some cases, intervening.

The team that is after the maintenance of the accelerator is composed of 30 people (including the nine operators) and is part of the Technical Department, the department that is in charge of the synchrotron, the building and the plants. The remaining part of the Department includes 10 people: four are after the IT infrastructure and six are after the building and the plants.

Differently from the accelerator, the maintenance of the plants is managed mainly through contracts with service companies, but the plants maintenance team is precious in this case as well. In fact, the plants here have been designed with as much redundancy as physically possible; some of these redundancies are automatic (for instance, each pump is duplicated and the Building Management System starts the second one as soon as the first has problems), other require a human intervention. The plants maintenance team knows how to manage these redundancies in the event of a failure allowing the operation to proceed as smooth as possible; the external company can then come to fix what has failed in the following days.

The data collected after more than 10 years of operation demonstrate the effectiveness of this approach: Table 1 shows the number of sessions lost because of technical reasons in the last five years, divided per system and per year. From 2011 to 2023 the system reliability, measured as the percentage of treatment days that have been completed with respect to the expected ones, is 98.7%.

Fig. 5 Render of the CNAO facility after the completion of the expansion works

5 A glimpse into the future

Not only the synchrotron is constantly evolving, but also CNAO itself is undergoing important renovations. The most relevant is a completely new wing that will house two other accelerators: a proton therapy single room facility with a rotating gantry and an accelerator for Boron Neutron Capture Therapy. This machine is a pioneering project that aims at making this very promising therapy something practical and widespread. Figure 5 shows a render of the facility in the final configuration.

The installation of the two machines will start in February 2024, in parallel with the completion of the construction works, which are expected to be completed in the first half of 2024. The new accelerators should be operational by mid-2025.

6 Conclusions

The CNAO facility treats various types of radio-resistant tumours with proton and carbon ions beams. The synchrotron used to accelerate these beams was designed, installed and now run and maintained by CNAO itself. This paper briefly described how the facility is operated and maintained by the Technical Department. In the coming months, CNAO will start the installation of two additional accelerators, thus expanding its treatment possibilities.

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Declarations

Ethical approval No Ethical Approval was required for this article.

Consent to Participate No Consent to Participate was required for this article.

Consent to Publish No Consent to Publish was required for this article.

Competing interests The author(s) have no competing interests.

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