

## THE EXPERIMENTAL BEAM LINE AT CNAO

M. G. Pullia, S. Alpegiani, J. Bosser, E. Bressi, L. Casalegno, G. Ciavola, M. Ciocca, M. Donetti, A. Facoetti, L. Falbo, M. Ferrarini, S. Foglio, S. Gioia, V. Lante, L. Lanzavecchia, R. Monferrato, A. Parravicini, M. Pezzetta, C. Priano, E. Rojatti, S. Rossi, S. Savazzi, S. Sironi, S. Toncelli, G. Venchi, B. Vischioni, S. Vitulli, C. Viviani, CNAO Foundation, Pavia, Italy

Mario Del Franco, Consorzio Laboratorio Nicola Cabibbo, Frascati, Italy

A. Lanza, INFN, Pavia, Italy

S. Giordanengo, INFN, Torino, Italy

A. Clozza, E. Di Pasquale, A. Ghigo, L. Pellegrino, R. Ricci, U. Rotundo, C. Sanelli, G. Sensolini, M. Serio, INFN/LNF, Frascati, Italy

L. Celona, S. Gammino, S. Passarello, INFN/LNS, Catania, Italy

R. Sacchi, Torino University, Torino, Italy

G. Battistoni, Università degli Studi di Milano, Milano, also at INFN, Milano, Italy

### Abstract

The CNAO center has been conceived since the beginning with three treatment rooms and an “experimental room” where research can be carried out without hindering the clinical activity. The room itself was built since the beginning, but the beam line was planned at a second moment in time to give priority to the treatments.

The experimental room beam line has now been 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, development of in-beam monitoring devices or radiation hardness studies.

In a second stage a third ion source will be added to the present two in order to carry on experiments with additional ion species besides the two used presently for treatments, protons and carbon ions.

In this paper a description of the design and of the construction status is given.

### INTRODUCTION

The CNAO (National Center for Oncological Hadrontherapy) in Pavia is one of the five 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 [1].

The CNAO synchrotron can accelerate ions injected with an energy of 7 MeV/u up to the energy corresponding to the magnetic rigidity of 6.35 T m. For  $C^{6+}$  ions this corresponds to 400 MeV/u; in the case of protons, the maximum energy of 250 MeV corresponds to a magnetic rigidity of 2.43 T m, well below the technically achievable maximum. For other ions, possibly produced with a dedicated third source, the maximum rigidity would still be 6.35 T m and the corresponding particle range would be determined by their charge and mass.

The CNAO was conceived since the beginning to be equipped with an experimental beamline in addition to the treatment ones and the experimental room (XPR) was

constructed since the beginning even if the beamline-construction has been postponed to give priority to the treatments. The present layout is shown in Fig. 1 together with the regions to be modified.

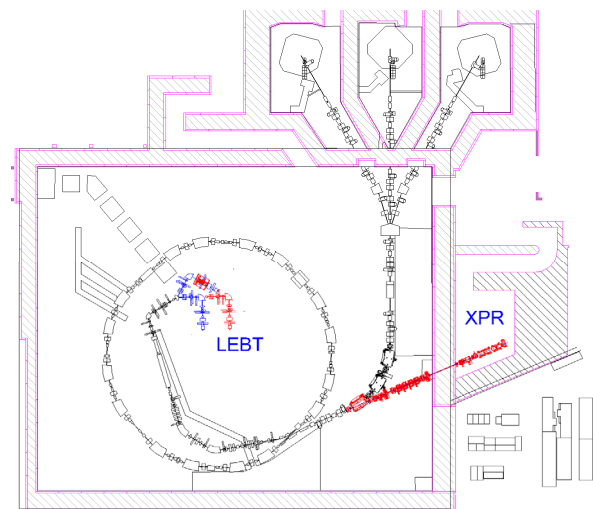


Figure 1: Layout of CNAO. The present Low Energy Beam Transfer line (LEBT) and the path of the experimental beamline are visible in blue; in red the new layout being implemented.

The functional specifications for the XPR have been defined also by means of an online survey directed to the community of possible users. More than 100 answers have been collected. Based on the functional specifications a design has been carried out and is now being built at CNAO [2].

### 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 various configurations. In the first case the irradiation point is as downstream as possible in order to get the maximum irradiation field; in this case the complete

beamline is installed but the distance between the irradiation point and the wall is only 40 cm.

In the opposite case, 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  $135 \times 135 \text{ mm}^2$  which satisfies the request of 93% of the answers to the users survey. A fourth configuration allowing beam monitoring in the most upstream position completes the possibilities as illustrated in Fig. 2 hereafter.

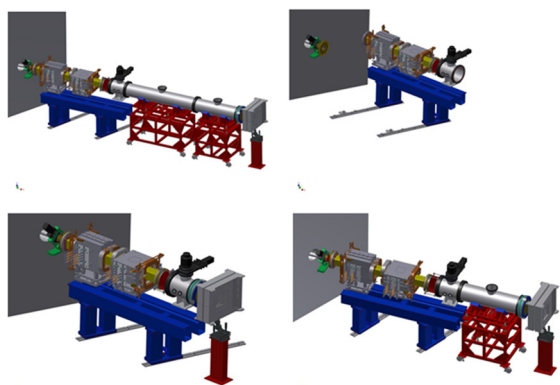


Figure 2: Four different configurations of the beamline in the XPR are foreseen.

### THIRD ION SOURCE

As anticipated, additional ion species shall be foreseen. Most of the users required light ions and just a few suggested to foresee heavier species like e.g. Fe or Xe. It has therefore been decided to specify that in the experimental room it shall be possible to use light ions with  $Z \leq 8$ , starting with He, Li and O.

Concerning intensity and energy of these species, the survey indicates that “clinical” intensities or lower should be foreseen and that a particle range of 300 mm would be suitable for most of the users. 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, as summarized in Table 1 and Table 2.

Table 1: Species Requirements, Phase 1

	H	He	Li	C	O
Z	1	2	3	6	8
I ( $10^8$ p/s)	100	25	11	2.8	1.6
K (MeV/u)	250	261.4	253	400	400

Table 2: Species Requirements, Phase 2;  
Same Units as in Table 1.

	H	He	Li	Be	B	C	N	O
Z	1	2	3	4	5	6	7	8
I	100	25	11	6.3	4	2.8	2	1.6
K	330	400	400	400	400	400	400	400

### PARASITIC OPERATION

During day time, the CNAO accelerator is dedicated to clinical operation and during nights the daily QA is carried out. This leaves only a small amount of time to be devoted to experimental activities in the experimental room.

It may happen that patient positioning and alignment take longer than desired and consequently there are times in which the accelerator is waiting to be used.

In these cases the beam can be directed to the experimental room in an automated way and the irradiation in the XPR will be automatically paused as soon as the beam is requested in a treatment room. The irradiation in the experimental room will be recovered automatically as soon as the beam is available again and provided the particle in use is still the same.

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.

### BEAM OPTICS AND BEAM MODEL

The beam is extracted from the CNAO synchrotron by a third integer resonant slow extraction according to a "momentum-amplitude selection" scheme in which the beam is driven into the unstable region by a "betatron core" [3]. The extracted beam distribution is along the extraction separatrices and is generally referred to as "bar of charge". Particles with different betatron oscillation amplitudes are extracted along different separatrices with different momenta and with different spiral steps.

The CNAO beamlines were designed using the same approach used in PIMMS considering an empty ellipse with emittance of  $5\pi \text{ mm mrad}$ , 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.

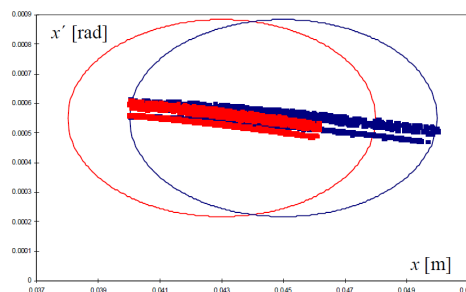


Figure 3: Bar of charge and empty ellipses for minimum and maximum  $\Delta p/p$  of the extracted beam. The red bar of charge corresponds to  $\Delta p/p = -0.001$  and the blue one to  $\Delta p/p = 0.0$ .

It is possible to obtain  $D_x=0$  or  $D'_x=0$  at the irradiation position, but not both at the same time.

Since the extracted beam momentum spread is in the order of 0.1% and the corresponding range variation is in the order of 0.05 g/cm<sup>2</sup>, it has been chosen to neglect the correlation between position and range with respect to the Bragg peak thickness, which is eventually enlarged artificially by means of ripple filters.

Neglecting such a correlation and recalling that there are no dipoles in the XPR beam line, the beam size increase due to momentum spread can be considered as emittance, as illustrated in Fig. 4.

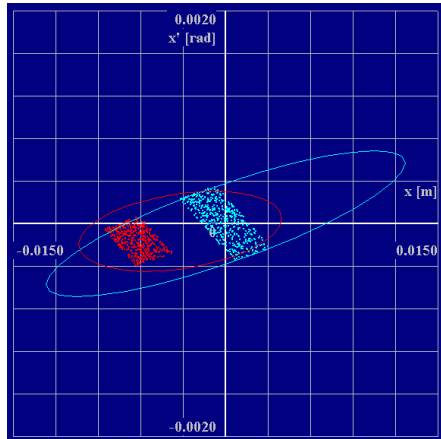


Figure 4: Bar of charge for  $\Delta p/p = -0.001$  (red) and  $\Delta p/p = 0.0$  (blue) at the entrance to the first HEBT Quad. The red ellipse is "matched" to the beam distribution and the blue one is the nominal empty ellipse.

The XPR beamline has thus been matched starting from Twiss parameters measured at the entrance to the HEBT and conservative emittance values. The resulting betatron functions are shown in Fig. 5.

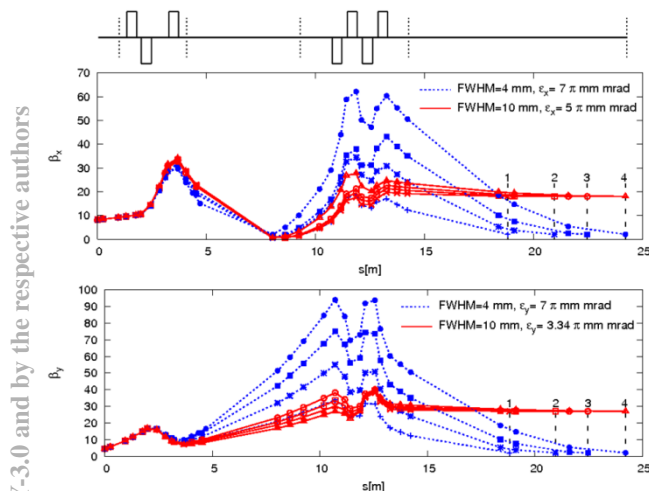


Figure 5: Betatron functions in the XPR beam line for small and large beam size at the four positions.

### HEBT CHOPPER

A very important element in the extraction line is the HEBT chopper which allows switching the beam on and

off in less than 200  $\mu$ s. 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 functionality, the chopper bump towards the XPR is created with two correctors and the only chopper magnet involved.

### 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 implies ramping 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 will therefore be carried out as much as possible during the periodic maintenance periods (3 days 4 times a year) or possibly during week-ends.

The beamline is presently in a procurement phase. Most of the orders and tenders have already been placed and delivery of the corresponding objects is expected within one year.

A few beamline elements are already in house and the first girder is being equipped and pre-aligned in a technical area outside the synchrotron hall to be ready for installation during one of the possible access times, see Fig. 6.



Figure 6: First XPR girder being equipped.

Concerning the building, as mentioned the room was built since the CNAO construction but a few works are needed including cabling and piping of the new beamline and of some ancillary systems.

### REFERENCES

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- [2] M. Pullia, C. Sanelli et Al, *Progetto della nuova facility di irraggiamento al CNAO*, INFN-14-09/LNF.
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