STATUS REPORT ON THE CENTRO NAZIONALE DI ADROTERAPIA ONCOLOGICA (CNAO)

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Abstract

CNAO is the first Italian center for hadrontherapy, presently in the initial commissioning and final installation stages. Proton and carbon ion beams will be used to provide treatments with active scanning. CNAO beams are generated by two ECR sources, both producing the two particle species. The beam energy in the Low Energy Beam Transfer (LEBT) line is 8 keV/u. Commissioning of the ion sources and of the injection line started in June 2008, and finished in January 2009, after 12 weeks of commissioning alternated with installation phases. The RFQ was thereafter installed, and commissioned in March 09. The LINAC is now being commissioned. The most relevant commissioning results are reported in this paper.

INTRODUCTION

The CNAO synchrotron will reach up to 400 MeV/u kinetic energy for carbon ions and up to 250 MeV for protons to treat deep seated tumours. Four treatment lines, in three treatment rooms, are foreseen in a first stage. For further details see Ref. [1] and [2].

The injection system of the synchrotron, placed inside the ring, is composed by an 8 keV/u LEBT, followed by an RFQ accelerating the beams up to 400 keV/u, a LINAC to reach the synchrotron injection energy of 7 MeV/u [3], and a Medium Energy Beam Transfer line (MEBT) to transport the beam to the synchrotron.

LEBT DESCRIPTION

General Layout

Two ion sources (called hereafter SO1 and SO2) are installed inside the ring. A solenoid is positioned next to each ion source. The first sections of the LEBT (O1 and O2) select the desired ion species (H_3^+ and C^{4+}) using the spectrometers and transport them up to the switching dipole from both the sources. The second and the third sections (L1 and L2), common to both lines, finish with a solenoid, positioned 48 mm upstream the RFQ. Figure 1 shows the schematic layout of the LEBT, with emphasis on the magnetic and diagnostic elements of the line. Along the line a quadrupole triplet in O1(2) and a quadrupole triplet in L1 are positioned for beam focusing and for transverse matching to the RFQ. A 75 degree dipole (with symmetric edge angles) is positioned in L2 section. Two horizontal and vertical steerers are positioned in each section of the LEBT. An electrostatic chopper is installed in L2 to form short beam pulses for acceleration in the LINAC and in the synchrotron.

Diagnostics

The diagnostics available in the LEBT [4] consist of wire scanners (BWS), slits (SLA) and Faraday cups (FCA). Horizontal and vertical beam profiles, positions and beam emittances can be measured both with wire scanners and slits. Ten diagnostic tanks are installed along the LEBT.

At the end of the LEBT a temporary test bench (used for the LEBT commissioning) with slits, wire scanners and a Faraday cup was installed downstream the final solenoid. This tank, called TB0, contained special slits that were positioned at the exact nominal entrance to the RFQ, wire scanners and a Faraday cup and it has been extremely useful to obtain the desired beam Twiss parameters for injection into the RFQ.

LEBT COMMISSIONING

The required current for C^{4+}, in order to have $4{\cdot}10^8$ carbon ions per extracted spill for the extraction lines (HEBT), is 200 µA, and the required minimum current for H_3^+, in order to have 10^{10} protons per extracted spill, is 600 µA. During the LEBT commissioning 230 µA of C^{4+} and 1400 µA of H_3^+ were obtained. The very efficient diagnostic instrumentation permitted to obtain a good steering along the LEBT. The transmission efficiency of the line is up to 97%.

Ion Sources

During the LEBT commissioning two weeks were dedicated to the acceptance tests of the sources (see Ref [5]). Both sources produced C^{4+}, H_2^+, H_3^+ and He^+.

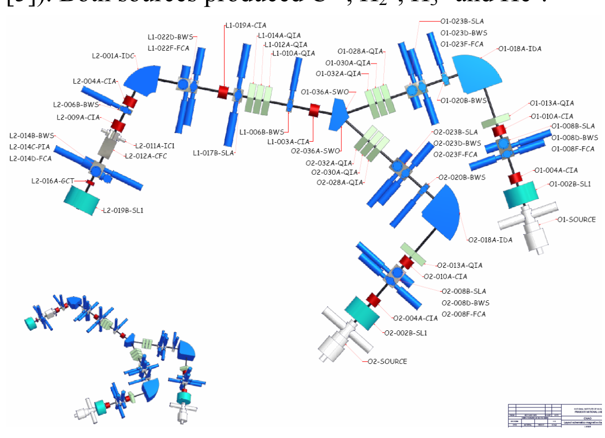

Figure 1: LEBT layout. Magnetic and diagnostic elements of the line are labelled.

The first measurements needed for source setup are the ion beam spectra. In order to perform the measurement, a ramp in current is sent to each spectrometer (O1(2)-018A-IDA) and the current variation versus time is acquired on the Faraday cup downstream the dipole. An example is shown in Figure 2, corresponding to the C^{4+} setup of the source SO2.

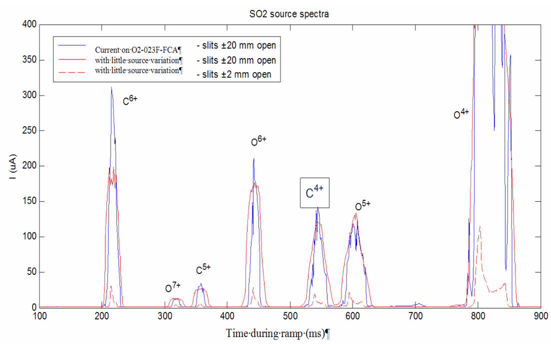

Figure 2: Beam spectra done ramping O2-018A-IDA spectrometer. The signal is acquired on the O2-023F-FCA Faraday cup.

Emittance Measurements

Some tanks of the LEBT (390 mm long) are equipped with horizontal and vertical slits, horizontal and vertical wire scanners and a Faraday cup. Typical emittance measurements performed along the line are shown in Figure 3 (that represents emittance measurements performed in O2-023B-SLA) and Figure 4 (that shows emittance measurements in L1-017B-SLA).

The nominal Twiss parameters necessary for a correct matching at the RFQ entrance are:

$\beta_{x,y} = 0.035$ m, $\alpha_{x,y} = 1.3$,

and the nominal geometrical emittance along the LEBT:

$\varepsilon_{x,y} = 180\pi$ mm mrad.

Measurements done on TB0, the tank placed at RFQ input position, are shown in Figure 5 and 6 (C^{4+} and H_3^+ respectively). It can be observed that the beam emittance fits well inside the yellow ellipse representing the theoretical RFQ acceptance.

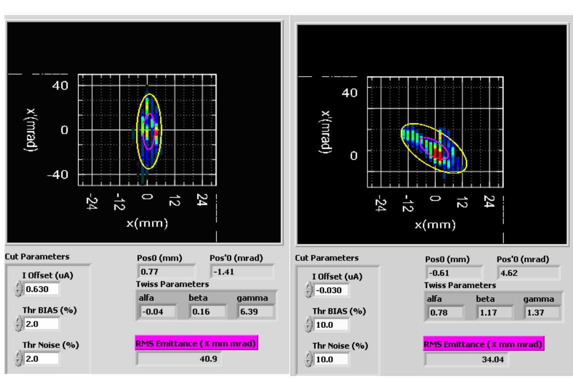

Figure 3: Horizontal (left) and vertical (right) emittance in O2-023B-SLA with C^{4+} beam.

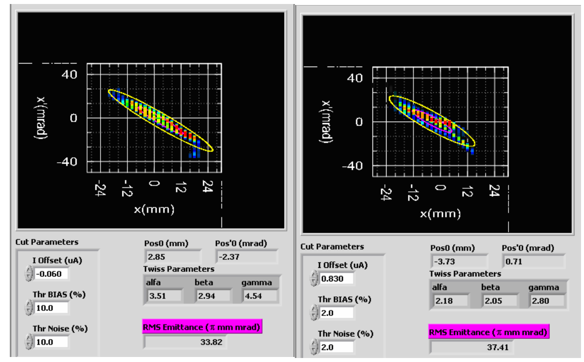

Figure 4: Horizontal (left) and vertical (right) emittance in L1-017B-SLA with C^{4+} beam.

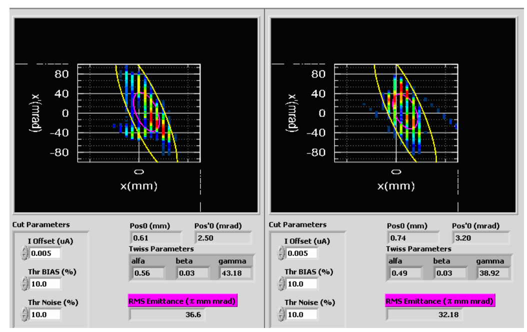

Figure 5: Horizontal (left) and vertical (right) emittance at the RFQ entrance with C^{4+} beam

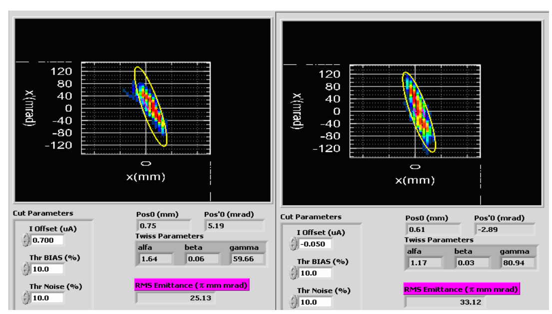

Figure 6: Horizontal (left) and vertical (right) emittance at the RFQ entrance with H_3^+ beam.

Transmission Along the LEBT

The transmission along the LEBT was up to 97%, after the steering procedure was applied, for both beams and both lines. The beam current was measured on three Faraday cups along the line which are also used as beam stoppers. A repeller ring electrode, in front of each cup, repels secondary electrons. Measurements with beam showed that a correct intensity measurement is made by setting the repeller voltage at -350V.

LEBT Modelling

Different set-ups of the LEBT optics have been tested during the commissioning, including an achromatic optics. Several emittance measurements were done varying the quadrupole currents of the line, and have been used to better define the LEBT optical model. The steering routine has worked both with calculated values and measured one, thus overcoming where needed the not perfect match between model and measurements.

RFQ COMMISSIONING

After the LEBT commissioning completion, TB0 was uninstalled and the beam was injected in the RFQ (see Figure 7). The measurements were done with H_3^+ and C^{4+} beams, at different LEBT beam energies, using a temporary beam diagnostic test bench (TB2), installed behind the RFQ (for further technical details about RFQ see Ref [3]). Transmission around 60% have been measured for both H_3^+ and C^{4+} beams. Higher and lower energies (7.5 and 8.5 keV/u) have been tested, but the design value of 8 keV/u has been found to be optimal.

In order to check the acceptance of the RFQ a 'probe beam' was prepared, that is a beamlet of much smaller rms emittance with respect to the nominal one (5π mm mrad versus 45π mm mrad). Using the L2 steerers and their previously measured response matrix, the 'probe beam' position in phase space at RFQ injection was changed and the transmission through the RFQ was measured. Figure 8 and Figure 9 show the horizontal and the vertical RFQ acceptance for a H_3^+ beam at 8 keV/u and at 8.5 keV/u, respectively. The measured acceptances are in good agreement with the calculated ones.

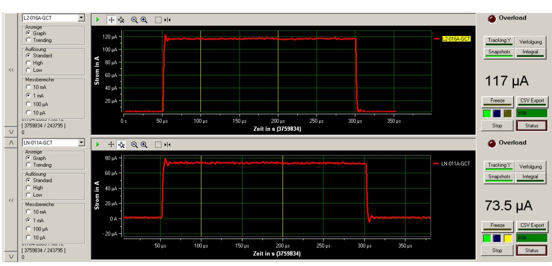

Figure 7: Current signals upstream and downstream the RFQ with C^{4+} beam at 8 keV/u and setting a non dispersive optics (achromatic) in L2. The beam pulses were formed by the electrostatic chopper in L2.

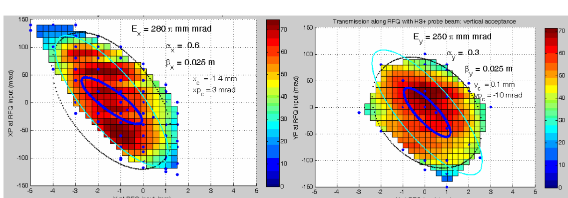

Figure 8: Horizontal (left) and vertical (right) RFQ acceptance measurements done with H_3^+ at 8 keV/u.

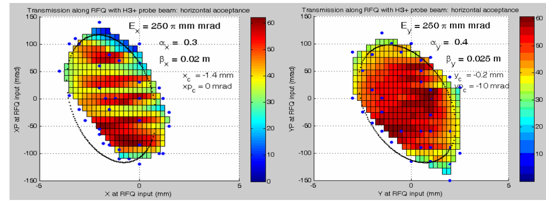

Figure 9: Horizontal and vertical RFQ acceptance measurement done with H_3^+ at 8.5 keV/u.

Emittances in TB2

The phase space distribution after the RFQ was investigated in TB2. Typical measurements are shown in Figure 10, with four times rms emittances (calculated for 90% of the beam particles) of 19.8π mm mrad (horizontal) and 15.4π mm mrad (vertical).

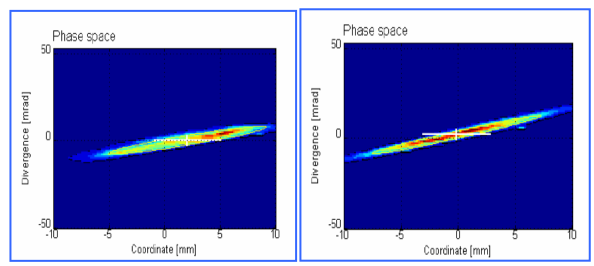

Figure 10: Horizontal (left) and vertical (right) emittance measured in TB2 with C^{4+} at 8 keV/u.

CONCLUSIONS

The first results of the CNAO commissioning are very positive. Good transmissions along the LEBT and through the RFQ have been obtained, thanks also to the excellent performances of the sources. CNAO commissioning is in progress and in June the LINAC tests will be done.

ACKNOWLEDGEMENTS

We are reporting the work done by the whole CNAO team, whose great effort and team working has allowed to start the machine commissioning in parallel with the installation activities. It was not possible to include all their names in such a short report, and we thank all of them for their contributions. Special thanks go to INFN, GSI and CERN laboratories for their help and collaborations.

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