CNAO SYNCHROTRON COMMISSIONING

Cristiana Priano, Giovanni Balbinot, Giulia Bazzano, Jacques Bosser, Erminia Bressi, Michele Caldara, Hervé Caracciolo, Luciano Falbo, Anna Parravicini, Marco Pullia, Claudio Viviani (CNAO Fondazione CNAO, Pavia, Italy), Caterina Biscari, Andrea Ghigo (INFN/LNF, Frascati, Italy).

Abstract

The CNAO (National Center for Oncological Hadrontherapy), located in Pavia, is the first Italian center for deep hadrontherapy with proton and carbon ion beams [1]. The CNAO synchrotron initial commissioning has been carried out using proton beams in the full range of energies: 60 to 250 MeV/u. The first foreseen treatments will need energies between 120 and 170 MeV/u. The nominal proton currents have been reached. The energy scaling of the synchrotron systems and parameters leads to an extracted energy that matches the measured particle range better than 0.1 mm, fitting the treatment requirements, with repeatable beam size and beam current in the treatment room at all investigated energies. A summary of the main results of the synchrotron commissioning is presented.

MULTI-TURN INJECTION

The CNAO [1] synchrotron is a 78 m long ring, in which the beam is injected at 7 MeV/u and accelerated to energies between 60 MeV, minimum energy for protons, and 400 MeV/u, maximum energy for carbon ions. The lattice is based on two symmetric and achromatic arcs joined by two non-dispersive straight sections.

MultiTurn injection (MTI) results in an injected beam which occupies all the synchrotron length (T_{rev} ~ 2µs). Pick-ups provide useful signals only after RF capture, but using a 1 µs chopped beam it has been possible to measure the beam position during the first turns, useful tool for the first commissioning period.

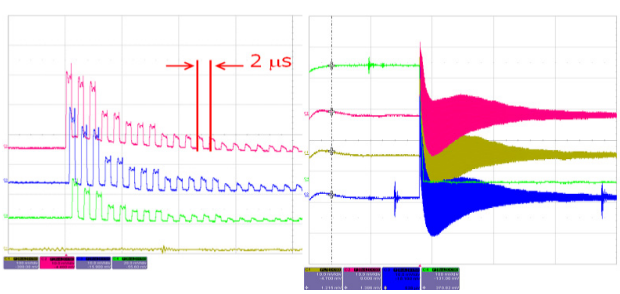

Figure 1 - Multiturn injection measured on three pick-ups without adiabatic trapping with 1µs beam and 30µs beam.

The design efficiency of MTI is 1.9 equivalent turns, that is the injected charge should be the one contained in 1.9 T_{rev} I_{MEBT}, ($1.4\ 10^{10}$ injected protons for I_{MEBT} = 600µA). The measured number of injected particles is much larger than the design one but there is a loss in the initial phase and during acceleration, which results in a number of accelerated particles equal to the specified one, with margin for improvement.

MACHINE CYCLE AND RF CAVITY

The machine cycle is designed to assure repeatability: the synchrotron magnets are ramped to their maximum field after every extraction, so that the same hysteresis loop is followed, independently of the beam extraction energy. Figure 2 illustrates the magnet cycle and the acceleration. The blue line represents the synchrotron dipoles field, the yellow one is the DCCT, the green one is the signal on a pick-up and the pink one is the voltage of the betatron core used for extraction. The DCCT rises quickly at injection, shows some losses during capture and acceleration and decreases linearly during extraction. The Pick-up signal disappears when the beam debunches as RF is switched off in preparation of extraction.

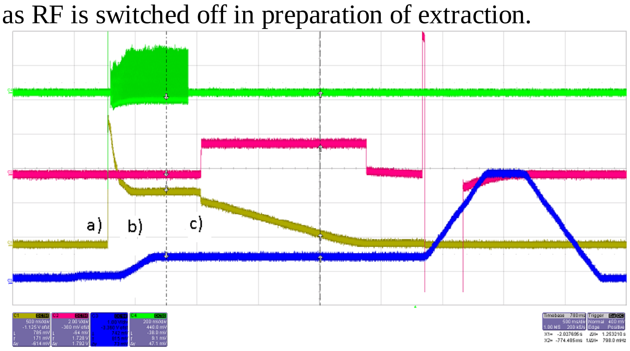

Figure 2: Signals shown on the control room scope: DCCT, B field, Pickup, Betatron core voltage. The main machine cycle phases are identified: a) injection, b) acceleration ramp, c) start extraction.

The RF cavity [2] has played a fundamental role in the synchrotron and extraction lines commissioning. It controls the beams during the critical moments of the whole cycle. After the multiturn injection the beam is unbunched: an adiabatic capture is performed controlling with precision the cavity voltage at low values (20-150 V), to avoid increasing longitudinal emittance. During the acceleration beam loops implemented in the low level RF damp the synchrotron oscillations fixing the beam energy despite possible irregularities in the dipole ramps[3] by controlling the beam phase and position in a high dispersion pick up. When acceleration is completed, the RF cavity finely adjusts the beam energy (in the range of $\Delta p/p \sim 10^{-3}$).

Before RF switching off to debunch the beam, the RF phase jump is used to increase the beam energy spread up to the extraction value with a uniform distribution. During extraction, the technique of empty bucket channelling reduces the ripple spill [4].

OPTICS MEASUREMENTS

Optics measurements in the synchrotron have been carried out at different energies. In this section we summarize the most significant, underlining the agreement with the optical model.

Dispersion

The dispersion function is determined by measuring the beam displacement with a typical RF frequency change, Δf_{RF}, of the order of a few kHz. The corresponding beam displacements in the high dispersion (D = 8.5m) pickups is of few tens of mm without significant beam losses.

$$D = \eta \frac{\Delta x}{\Delta f_{RF} / f_{RF}} = \left(\frac{1}{\gamma^2} - \frac{1}{\gamma_{TR}^2} \right) \frac{\Delta x}{\Delta f_{RF} / f_{RF}}$$

Figure 3 shows the dispersion measurements at various energies, matching very well the dispersion calculated from the synchrotron model.

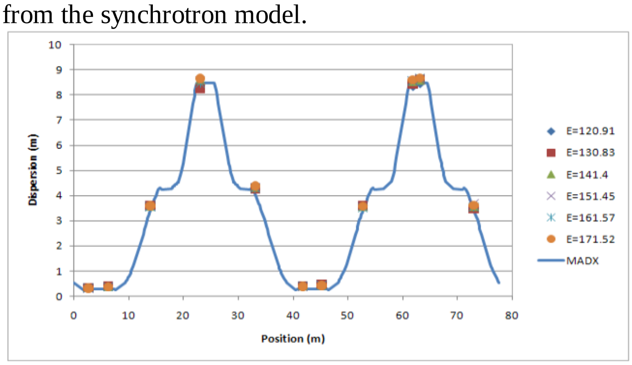

Figure 3: Horizontal dispersion measurements made at several energies compared with the theoretical value computed with MADX.

Tune and Chromaticity

The betatron tune measurement system consists of a fast horizontal and vertical kicker magnet and two dedicated pickups (H and V)[6].

The integer part of the tune is 1 for both planes: Q_x~(1.66 – 1.68); Q_y~1.79.

The difference between the measured and the modelled tune is of the order of 0.01-0.02 on both planes. Since the extraction efficiency depends strongly on the horizontal betatron tune, the tune is placed on the extraction value with a precision of 10^{-4}, by fine tuning the three quadrupole families. The calculation of the tune variation as a function of the quadrupole strength variation is in fact excellent.

Chromaticity is measured by changing the energy with the RF frequency, similarly to the dispersion measurement, and measuring the tune in the various cases. The natural chromaticity ξ_x is the only optic characteristic significantly differing from the design: in the horizontal plane it turned out to be slightly positive, instead of the expected low negative value, presumably due to sextupolar terms in the dipoles. This behaviour repeats at all energies. In order to set the chromaticity at the negative extraction value, (Q'_x =-4), the two chromaticity sextupole families are now both defocusing. Figure 4 shows some measurements for different energies, covering the momentum range from the circulating beam up to the extracted beam.

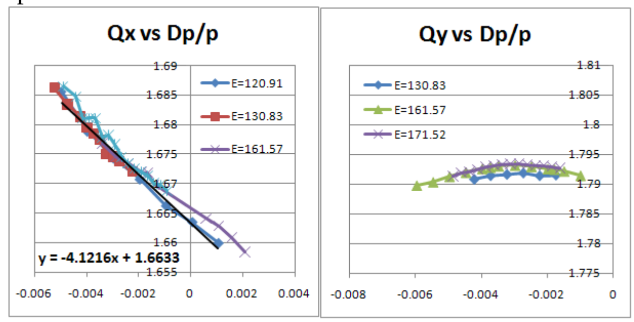

Figure 4: Horizontal (left) and Vertical (right) chromaticity measurements for some proton energies.

The tune and chromaticity measured in the energy range from 120 to 170 MeV are similar: the scaling of the machine parameters with the energy is satisfactory.

Closed Orbit

The beam is injected, trapped, and accelerated with a momentum deviation with respect to the dipole setting of ~ -2.5 10^{-3}. The horizontal Closed Orbit (CO) is therefore dominated by the dispersive contribution. Figure 5 shows the orbit in the pickups along the whole cycle. The alignment of the synchrotron magnetic elements is satisfactory: no steerers are needed to store and accelerate the beams. The peak horizontal CO, subtracting the dispersive part, is 2 mm, while the vertical one is 8 mm, which can be easily corrected with a single steerer. Both are shown in Figure 6.

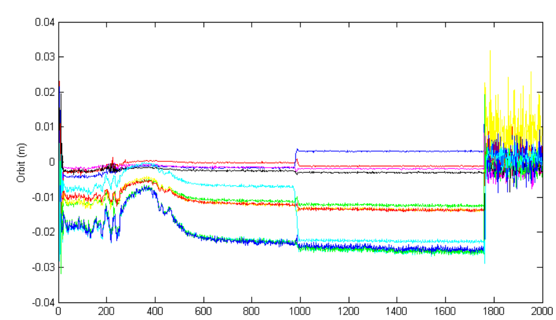

Figure 5. Closed orbit measurements along one cycle in the different horizontal pickups.

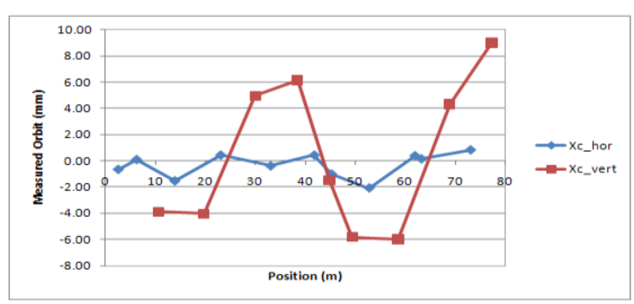

Figure 6. Closed orbit in the ring without steerers. In the horizontal plane the dispersive contribution is subtracted.

Response Matrix and Orbit Control

Transverse response matrices have been evaluated measuring the orbit variation due to a single corrector kick of 1 mrad. Figure 7 shows a measurement compared with the predicted orbit distortion computed by MADX. Energy correction as foreseen in [5] has to be considered:

$$\frac{\Delta p}{p} = \frac{1}{\alpha_C L} \Delta\vartheta \cdot D$$

where α_c is the momentum compaction factor, L the ring length, D the dispersion at the corrector, and $\Delta\theta$ the corrector kick.

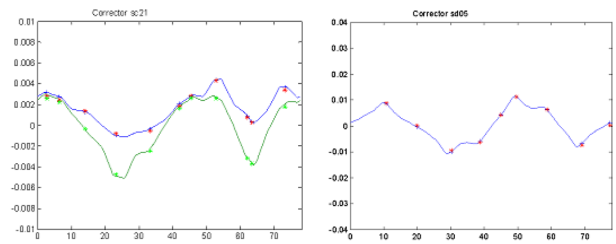

Figure 7: Measured and simulated response matrix in the horizontal and vertical plane.

A five-steerers bump is routinely used to optimize the beam position and angle at the electrostatic septum for extraction (whose transverse position turned out to be misplaced and will be modified in one of the next shutdowns) and at the magnetic septum. The reproducibility of the bump in the range of energies is shown in Figure 8.

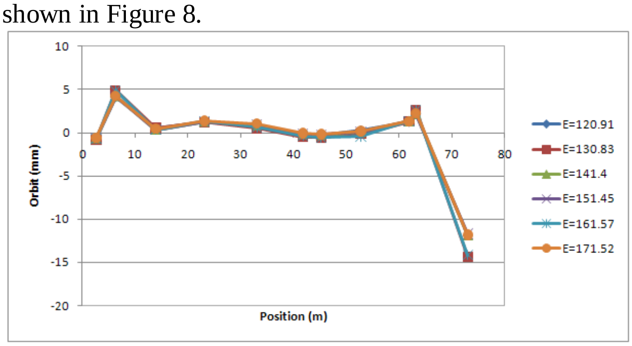

Figure 8: Horizontal closed orbit with the 5 magnets bump, for 6 beam energies between 120MeV to 170MeV.

Betatron Functions

The betatron function measurement at the synchrotron quadrupoles sites is done through a static variation of each quadrupole strength (Δk) and the measurement of the subsequent tune shift ΔQ.

In the synchrotron the 24 quadrupoles are divided into 3 families of 8 magnets. Each magnet is equipped with an extra coil connected to a separate power supply. One magnet at a time can therefore receive an additional current to provide the desired strength shift Δk [6].

Figure 9 shows the good agreement between the measurements and the values calculated from the MADX synchrotron model.

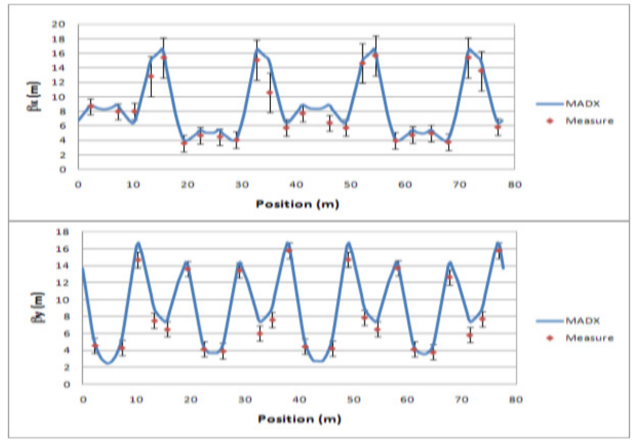

Figure 9: Measured and simulated (MADX) β_X and β_Y.

EXTRACTED BEAM

The extracted beam energy is determined by the measurement of the Bragg peak [4], with an accuracy of 0.1 mm in depth, corresponding in the present range of energies to about ~ 0.05 MeV.

A fine tuning and checking of the synchrotron dipole field, RF parameter set-up, beam position at the extraction septum, betatron tune and chromaticity has been carried out in the 100-200 mm range at 11 equally spaced depths, and then interpolated in 2 mm steps. The agreement between Bragg peak and synchrotron energies is within measurement accuracy. In order to obtain such a good agreement the energy at extraction is exactly controlled by the rf cavity, as said before, by modifying the RF frequency, and therefore the dispersive part of the closed orbit. At the extraction position it corresponds to a difference of the order of 4 mm between minimum and maximum energy, and is thereafter taken into account in the HEBT steering correction procedure.

CONCLUSIONS

The CNAO commissioning for protons is finished and Carbon ions have been recently accelerated and extracted. Proton beams of the required energies and beam size have been produced and validated with measurements in the treatment rooms. Optical models of the machine have been developed that allow rescaling the machine for the desired energy. The repeatability of beam dimensions, position and energy in the treatment room is excellent.

Authorization to treat patient has been obtained and the clinical trials with protons will start very soon.

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