BEAM DIAGNOSTICS COMMISSIONING AT CNAO

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Abstract

The National Centre for Oncological Hadrontherapy (CNAO) [1] is the first Italian facility for the treatment of deep located tumors with proton and carbon ion beams using active scanning. The commissioning with proton beams is concluded and CNAO is going to start treating patients with protons; in the meantime the machine commissioning with carbon ions beam is going on. Beam diagnostics instrumentation is fundamental to measure beam properties along the lines from sources to patients. Some significant measurements performed during proton beam commissioning and the performances achieved with the CNAO beam diagnostic systems are presented in this paper.

BEAM DIAGNOSTICS OVERVIEW

Along all the way between the sources, where it is produced, and the treatment room, where it is destroyed, the beam characteristics change pretty much under all the aspects. The beam instrumentation needed to measure the quantities of interest has therefore to change as well.

In the LEBT, is present a low energy (8keV/u) continuous beam, with intensities in the order of a few 100s of μA and emittances in the order of 180 π mm mrad. To measure such a beam a compact and efficient measurement station has been developed which includes horizontal and vertical slits, horizontal and vertical wire scanners and a Faraday cup. The complete tank occupies 390 mm in length and allows measurement of beam current, position and phase space distribution. The CNAO LEBT is equipped with 4 complete tanks plus a few wire scanners, [2]-[3].

At the end of the LEBT, the beam is chopped in order to send beam to the LINAC only when it is needed for injection, that is only a few 10s (30 μs nominal) of μs every 2-3s.

The beam is then measured with a fast current transformer and with profile grids, which are compatible with a pulsed beam.

The CNAO LINAC is composed by a RFQ and a IH-DTL working at 217MHz. The LINAC beam is therefore made by 30 μs pulses with an internal structure at 217MHz. The output beam energy is 7MeV/u, [4]

In the following line (MEBT), the instrumentation includes Faraday cups and fast current transformers for current measurement, phase probes for energy evaluation, a special pick-up for position and profile grids for profiles. A couple of slits is present in the line for particle selection which can also be used for diagnostic purposes.

At injection in the synchrotron a couple of luminescent screens are used to measure the beam at the synchrotron entrance and at the end of the first turn.

Closed orbit measurement in the synchrotron is guaranteed by 10 horizontal and 9 vertical pick-ups. The beam energy in the accelerator varies between 7 MeV/u at injection to 250 MeV for protons (400 MeV/u for carbon ions) with revolution frequencies in the range 0.5-3 MHz and currents in the order of 1mA.

The beam current is measured with a DCCT and a couple of Schottky PUs provide information on the beam frequency distribution.

Horizontal and vertical scrapers are present to suppress beam halo and to scrape the beam to the desired emittance. They are placed in a dispersion free region and can be used to measure beam profiles of the circulating beam and therefore to estimate the beam emittance when the betatron functions are known.

A couple of fast magnets is installed to measure the tune (tune kickers). The CNAO Pick-Ups have a large enough bandwidth to measure the resulting oscillation with a dedicated electronics or on a scope.

Finally the beam is extracted to the treatment rooms over a large energy range (60-250 MeV/120-400 MeV/u) and over a large current range (4 10^6 to 10^{10} pps).

The extraction lines are equipped with scintillating fibre harps acquired with CCD cameras. Fibres are 0.5 mm wide, but are binned 2 by 2, providing a spatial resolution of 1 mm. The extracted beam has a nominal length of 1s and the maximum profile acquisition rate is 50 Hz.

MEASURE OF β FUNCTION

The beta function measurement at the synchrotron quadrupoles (β_Q) sites is achieved through a static variation of quadrupole strength (Δk) and the measurement of the subsequent tune shift ΔQ. The two quantities obey to the law

$$\beta_Q = \frac{4\pi}{\Delta k \cdot L_q} \Delta Q \quad , \tag{1}$$

where L_q is the quadrupole magnetic length. The aim of the measurements is to obtain for each quadrupole a set of data $(\Delta k;\ \Delta Q)_i$, where Δk is not measured but estimated through the relation $\Delta k/k_0 = \Delta I/I_0$ (I_0 is the current of the main coil, k_0 is the nominal strength of the quadrupole, ΔI is the current variation), and ΔQ is obtained as the difference of $Q(I_0+\Delta I)$ and the unperturbed machine tune $Q(I_0)$. The tune measurement is performed using a system based on the principle described in [5]. The β_Q values are eventually obtained via linear regression from the sets of data $(\Delta k;\ \Delta Q)_i$. Figure 1 and Figure 2 show, respectively, the absolute value of the horizontal and vertical beta function with their error bars measured with the reported technique during extraction at flattop and compared to the madX calculation. The measurement uncertainty for the

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two sets of data is approximately ± 1m and depends on the tune measurement uncertainty and the statistics collected.

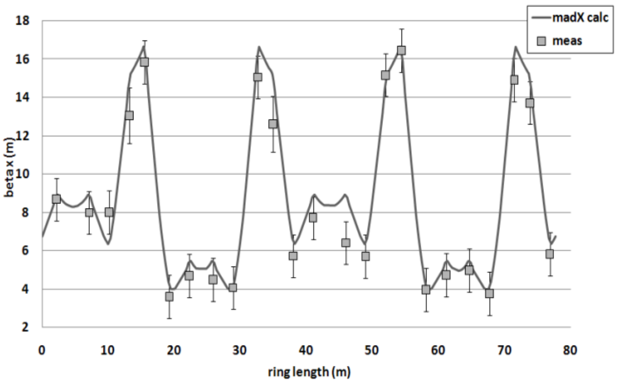

Figure 1: Absolute value of horizontal beta function along the synchrotron ring at extraction.

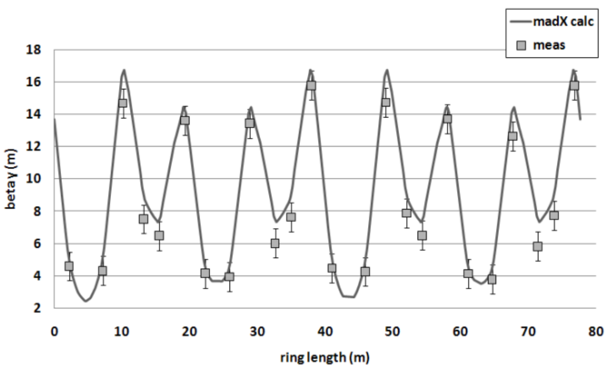

Figure 2: Absolute value of vertical beta function along the synchrotron ring at extraction.

AMORPHOUS SILICON DETECTOR

Just upstream of the CNAO extraction magnetic septum, a detector is installed to monitor particle that are lost on the septum coil. This detector is made of hydrogenated amorphous silicon (a-Si:H [6]) and the prototype was produced at "Institut de Microtechnique" (EPFL, Switzerland) under CNAO specifications. The sensor thickness is 5 µm, deposited on a 500 µm glass substrate. Figure 3 shows the detector mechanics on left and the cross section layout with all layers, on the right. The noise current is in the order of 2e-10A with -1V of polarization and it is due to the pair generation-recombination effect in the depletion zone. The detector has been tested with proton beams at the isocentre to evaluate its performances. Figure 4 depicts the total charge collected versus the polarization voltage. Being the beam fixed, the effect of increasing the detector reverse voltage is to improve the collection efficiency of the generated charge into the depletion zone. The beam on the detector is 173.3MeV with 2e8 protons and the detector polarization voltage is -1V. As explained at the beginning of the present paragraph this detector is foreseen to be used, not at the isocentre but rather in the shadow of the extraction septum where only a small fraction of the extracted beam intensity is foreseen to be lost. Therefore in order to test

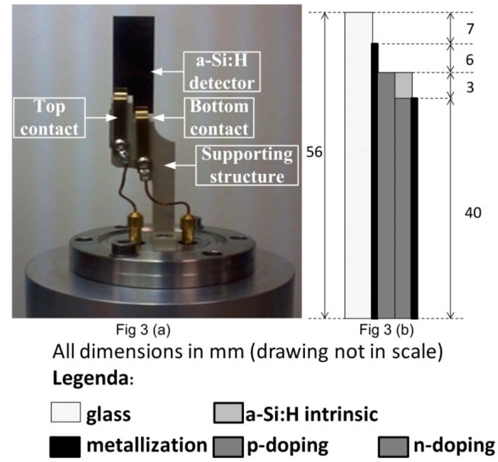

Figure 3: Detector mechanical assembly Fig. 3 (a), and detector cross section layout Fig. 3 (b)

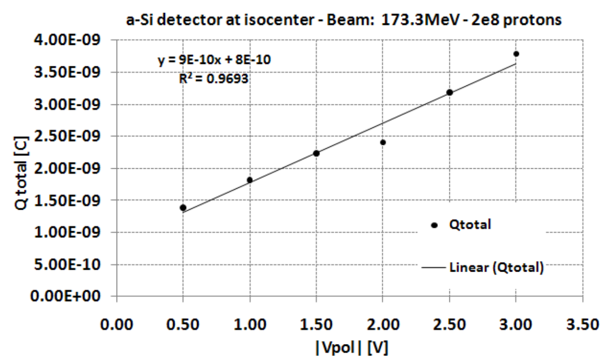

Figure 4: Detector generated total charge versus its reverse voltage.

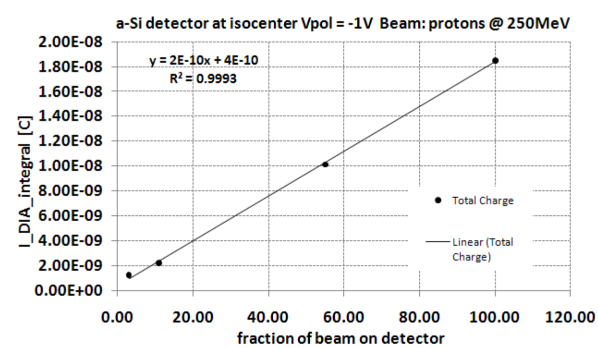

Figure 5: Total collected charge versus fraction of beam hitting the detector.100% corresponds to 2e9 protons.

the reading resolution of the system, the beam was set at maximum energy and then the number of particles has been progressively reduced. Figure 5 represents the collected charge varying the number of particles with proton at 250 MeV using a polarization of -1V. Full beam on the detector is 2e9 protons (nominal maximum full beam in synchrotron is 1e10 protons, but however the detector installed on septum is never hit by 2e9 particles during the extraction). It can be noted that the detector is able to measure even the minimum number of particles at maximum beam energy, and plotting the total charge generated in function of the total number of particles,

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measured with the DC current transformer, we obtain a good straight line. After these preliminary tests the detector has been installed on the magnetic septum. Figure 6 illustrates the particles loss during the extraction at 117.8MeV with a polarization of -1V: at t = 0s the betatron switches on and the current on the detector has a maximum, and at t = 1s the extraction finishes and the current becomes equal to the noise at t = 1.5s. Using the results achieved with the test at the beam isocentre, the estimated particles loss on the detector is 1.3e7 protons.

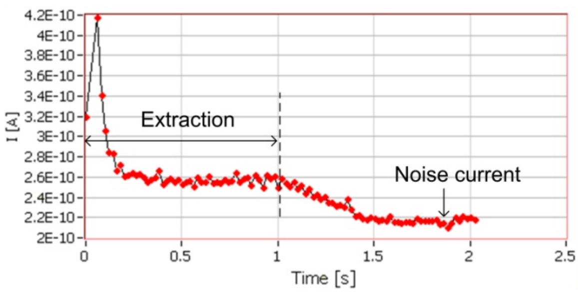

Figure 6: Detector current during the extraction.

SERVO-SPILL LOOP ON AIR CORE QUADRUPOLE

A servo-spill loop on the ACQ is implemented to reduce extracted beam intensity ripple. Figure 7 depicts the system block diagram. The signal of an intensity monitor in the HEBT is acquired and the software proportional integrator (PI) control generates the signal to drive the ACQ power supply. The servo spill system presently works in a closed loop on the Qualification Intensity Monitor (QIM) [7].

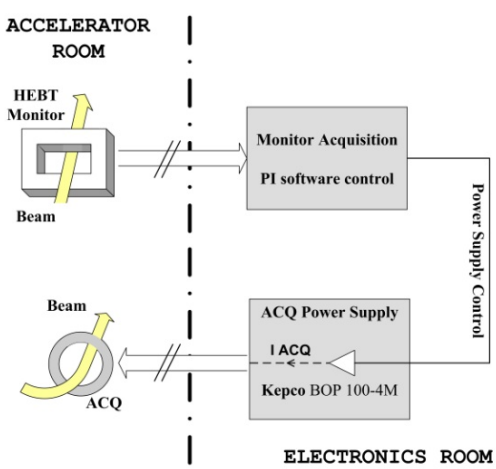

Figure 7: Servo Spill on the ACQ block diagram.

The acquired QIM intensity signal is processed in a software PI controller and the output is sent to the ACQ power supply. Figure 8 shows the intensity signal on the QIM. From t = 0s and t = 0.5s the servo spill is off and the beam intensity has big ripple. At t = 0.5s the system is switched on and the intensity ripple is strongly reduced. Figure 9 shows the FFT without (on top) and with the close loop (on bottom) displaying the suppression of the low frequency harmonics. The FFT is made on the QIM signal with proton beam at 117.8MeV. The next step is to use the dose delivery monitor signal to close the loop. In the next future studies are foresee on an "a-Si:H" intensity monitor having a thickness of about 10µm.

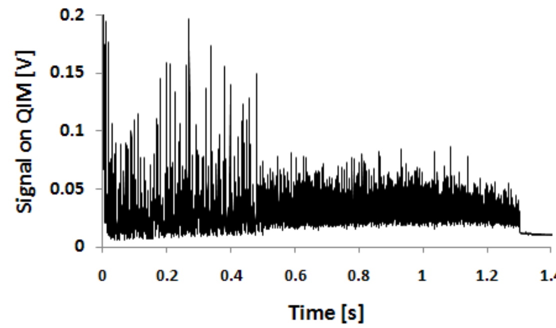

Figure 8: Intensity signal on the QIM. At t = 0.5s the servo spill loop is switched on and the intensity ripple is reduced.

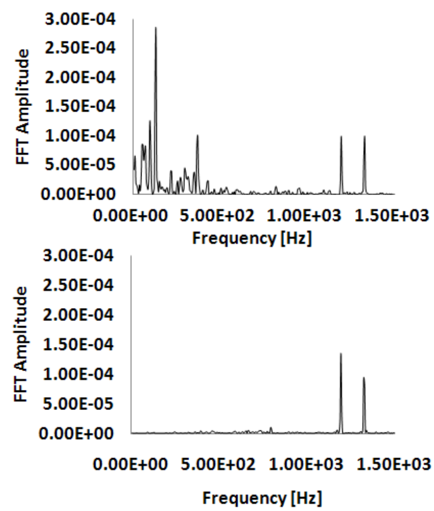

Figure 9: FFT on the QIM signal without correction on top and with correction on bottom.

CONCLUSIONS

This paper presents some results at the state of the art achieved by CNAO beam diagnostics systems. Beam diagnostics is essential to set accurately and in fast way the beam along the lines so to provide the patients with a beam fulfilling the treatment specifications.

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