OPTIMIZATION OF CARBON TREATMENTS AT CNAO

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Abstract

CNAO facility started treating patients with carbon ion beam in 2012. Carbon ions are often used to treat tumours with great volumes that cause long irradiations time: this represents an annoyance for the patient, a limit in the number of treatable patients per day and an increase of treatment cost. During last year, some effort has been put into to increasing the particle intensity in order to reduce the irradiation time for the carbon treatments: this article illustrates the changes in the machine set-up that were applied to achieve this goal.

CARBON TREATMENTS AT CNAO

CNAO Machine and Carbon Treatments

Hadronterapy treatments are presently performed worldwide using proton and carbon ion beams. The radiobiological properties of carbon and proton beams are different (LET, RBE, lateral scattering and so on) [1]. The choice of the particle to be used depends on many factors including the tumour histology and size. CNAO is one of the 5 facilities in the world able to treat cancer using both high-energy protons and carbon ions [2]. Ion beams are generated by two ECR sources (one for protons and one for carbon ions), accelerated by a 78 m synchrotron and delivered to 4 treatment lines. The machine size and many characteristics of its devices depend on the maximum energy of carbon beams that is 400 MeV/u (corresponding to 270 mm of range in water). Carbon beam has been commissioned in 2012 and it has been used to treat more than 700 patients (about 70% of all the treated patients) and several kinds of tumours (head-neck chordoma, sarcoma, prostate cancer etc.)[3]. Many of the tumours treated with carbon are large, causing long treatment sessions. A long irradiation time represents an annoyance for the patient and limits the number of treatments per day: for these reasons many efforts have been put into recommissioning the machine settings in order to reduce the duration of treatment cycle for the carbon treatments.

B-Train at CNAO

An important difference between the acceleration of proton and carbon beams at CNAO is the use of the B-Train system [4]. Usually with the name B-Train system one refers to a system that measures the magnetic field of the main dipoles of a ring and distributes this measurement to other systems (like RF cavity and beam diagnostics) to maintain the synchronism among all the ring devices. At CNAO the B-Train system has another important functionality: it uses the measurement of the magnetic field to correct the field itself, generating a feedback on the dipoles power supply. This feature is mandatory at CNAO because the setting time of the B-field in the CNAO dipoles at the currents needed for carbon is large on the time scale of the machine cycle(see Figure 1).

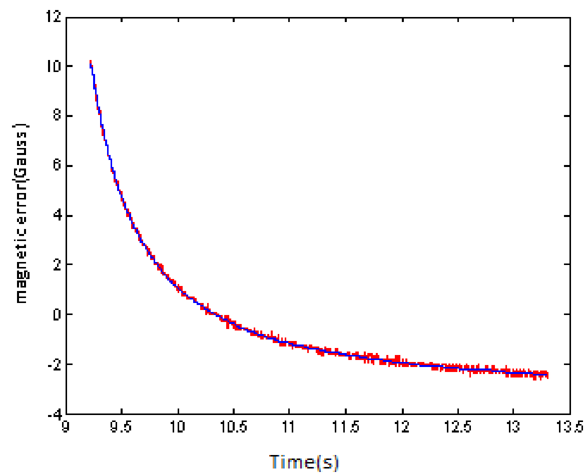

Figure 1: Trend of the magnetic field error after the dipole has reached the current to accelerate 400 MeV/u carbon beams without B-Train feedback.

CYCLE SHORTENING

Strategies of Shortening

A treatment cycle can be–subdivided in two parts: the extraction (*spill*), whose duration is between 100 µs and 3.5 s depending on the characteristics of the tumour, and the time needed to prepare the beam (*interspill*),. The *interspill* is made up of 3 parts: injection, acceleration and hysteresis cycle of the synchrotron magnets (*washing*). At injection all the magnets go to the value needed for the injection (*flatbottom* value), beam is injected (multiturn injection) and adiabatically trapped by the RF cavity. During acceleration all the magnets ramp from the injection current to the extraction current (*flattop* value) and finally some time is needed for the B field to stabilize at its final value. During washing all the synchrotron magnets ramp from the extraction value to a current larger than the one of carbon maximum energy and then back to minimum current. This allows the magnet to complete each time the same hysteresis cycle and it is needed to have a magnetic repeatability among all the different energies. For carbon, the original duration of the interspill was about 4.4 s. While for the injection part no time gain is possible the interspill can be reduced working on the acceleration and washing parts.

Acceleration Shortening

Acceleration has been shortened in two ways.

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First: in the original cycles the acceleration segment lasted 795 ms but the time really needed to accelerate the beam depends on the energy (420 ms for the lowest energy and 795 ms for the highest energy).

In the new cycles, the LLRF communicates to the other devices the end of the acceleration allowing extraction to be started as soon as possible.

Second: the time needed for field stabilization has been shortened working on the B-train feedback parameters.

These were originally the result of a compromise between the effect on the field delay and on the field ripple: a high loop gain_shortens the stabilization delay but it introduces large 40-60 Hz oscillations.

The adopted solution is to have feedback parameters that depend on the cycle part: during dipole ramp the feedback must be strong enough to minimize the field delay; when dipoles are at flatbottom or flattop the gain is reduced to minimize the effects on field ripple. The change from strong to weak is realized by suddenly switching the feedback sampling period (from 2 kHz to 500 Hz); the switch happens as soon as the flattop value is reached for the lower energies and 100 ms after the flattop value is reached for the higher energies. In this way the relative field error during extraction is less than 0.005%, which is a good value in terms of spill energy and position stability at the end of the line (*isocenter*). Figure 2 shows the field error from the beginning of the cycle up to *flattop*: one can see that after reaching the *flattop* an oscillation begins and it dampens 100 ms after *flattop,* when the feedback switch. These optimizations allowed to save 500 ms.

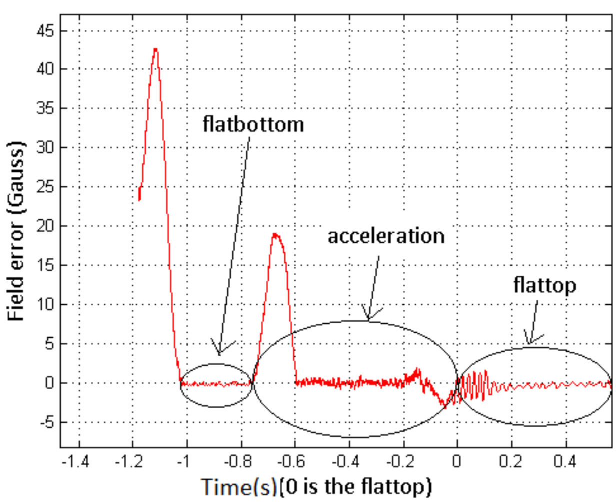

Figure 2 : Magnetic field error from the beginning of the cycle to the extraction under the influence of the B-Train feedback.

Washing Shortening

To shorten the *washing* part of the machine cycle, the time needed by the magnets to complete their hysteresis cycle was reduced. For all the magnets, except the dipoles, the solution was to increase the speed of the washing ramp: this causes a higher than usual current error during the washing that anyway does not affect the effectiveness of the washing. For the dipoles increasing the ramp rate was not possible. The B-Train feedback has been then used also to regulate the B field during the ramp down, completely avoiding the ramp up to the maximum magnetic field. Indeed, since the B-Train guarantees a continuous feedback on the magnetic field, the dipole current can go directly from the extraction current to the injection current without magnetic hysteresis problems.

Ghost Beam Problem

Figure 3 shows the *interspill* duration at the different energies with the new cycles and the one with the old cycles.

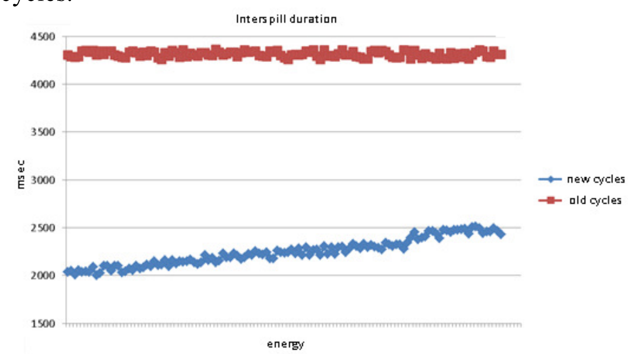

Figure 3 : Comparison between the interspill of the old and the new cycles versus the different carbon energies.

The beam characteristics (energy, position, size) measured at the isocenter were found to be within clinical specifications. However, an accurate analysis of the spill structure revealed a problem that needed some refinements in the cycle structure described above.

At CNAO, beam is extracted by a third order resonant mechanism [5] and then transported to the patient through a high energy transmission line (*HEBT*) [6]. The HEBT contains an important element for the patient security and the management of the dose during treatments: the so called HEBT chopper it is made up of four fast dipoles (100 µs) fed in series according to the scheme ("+B, -B, -B, +B"). When the magnets are switched off, the beam is stopped by an internal dump. When the magnets are switched on, the beam is deflected, it avoids the dump and reaches the treatment room. The status of the HEBT chopper is controlled by the dose delivery system that monitors in real time the dose delivered to the patient. When the chopper is closed the beam that strikes the HEBT dump can be measured with a dedicated monitor (QBM) that can be put "in the line" (i.e. in the beam path towards the patient) or out of the line (in front of the dump) [7]. This monitor is made up of a fast (up to 10 µs acquisition rate) intensity monitor (QIM), and a scintillating fiber profile monitor (QPM). In other words when QBM is in the line, it measures the beam that can reach the patient (HEBT chopper on), when it is out the line it measures the beam that goes to the dump (HEBT chopper off). During beam extraction at a given energy, when all the needed dose has been delivered, the dose delivery system switches off the HEBT chopper to stop the irradiation; the beam that is not extracted and is still circulating in the synchrotron, dies in the radial dump of the synchrotron itself during the washing cycles ("partial extraction"). Using the new short cycles a unexpected behaviour appeared in case of partial extraction: the QBM measures some beam in the line after the end of the irradiation, even if the chopper is off. This unexpected beam was called "ghost beam". The characteristics of the ghost beam are the following:

- The intensity depends on energy and is similar to the nominal
- The duration is in the range 2-20 ms and increases with energy.
- It appears 10 ms after the beginning of the washing cycle.
- It is measured both when the QIM is "in" and when it is "out".
- The beam profile is larger with respect to the normally extracted beam in both transverse planes.

Figure 4 and Figure 5 show respectively the QIM acquisition and QPM acquisition when the monitors are "in".

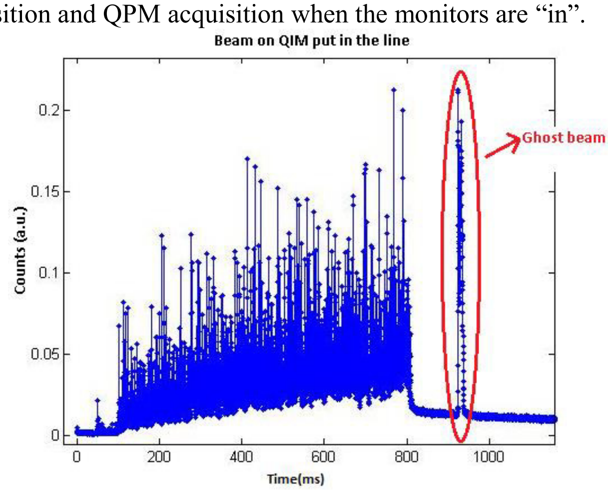

Figure 4: Beam on QIM put in the line for the 400 MeV/u carbon beam.

The ghost beam is obviously generated by the new washing mechanism, thus several measurements have been carried out for different washing setups (speed, level and delay of the various magnets). The result of these measurements showed that ghost beam depends on the relative washing timing of the dipoles and the quadrupoles. When the dipole field goes directly down, the beam goes towards the outer part of the ring where the electrostatic septum is positioned to capture and extract the beam. Even if geometrically the beam should die in the radial dump, the tune changes, the beam crosses resonances and part of it is thus extracted. The survival time of the beam in the synchrotron increases with energy with the same trend of the time duration of the ghost beam. The washing speed of the synchrotron quadrupoles was further increased and the dipoles were ramped at a current 2% to 3% higher than the extraction value before returning to the minimum current. In this way the beam can die hitting the dump that is on the opposite side with respect to the electrostatic septum.

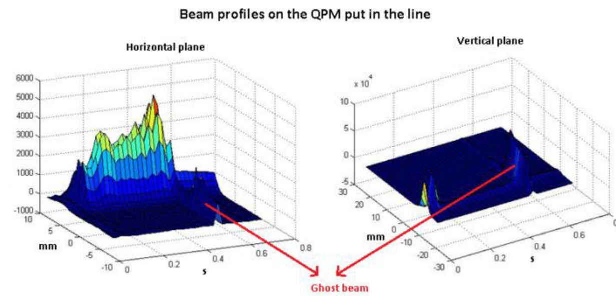

Figure 5: Horizontal and vertical profiles of the 400 MeV/u carbon beam measured by the QPM put in the line.

CONCLUSION

In the last 4 years, carbon beams have been widely and successfully used at CNAO for several kinds of tumours. Several measurements and machine optimization have been performed in order to shorten the machine cycle, creating a great advantage for the patients and for the machine: with the new cycles the duration of a typical treatment has been reduced by about 40% and its cost has been reduced by about 20%.

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