IMPROVEMENTS ON CNAO ACCELERATOR FOR OCULAR TREATMENTS

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Abstract

Ocular melanoma has been successfully treated worldwide since many years using proton beams. CNAO is the only Italian hadrontherapy facility able to treat tumours with both proton and carbon ion high-energy scanning beams accelerated by a synchrotron. The machine was commissioned in 2011 and more than 1000 patients have been treated so far. With respect to the other cases, ocular melanoma treatment needed important changes under both the medical physics and machine physics points of view. The main goal of this work is to describe the changes in the machine set up to increase the proton current by a factor of 5, this task representing a sort of re-commissioning of the synchrotron.

OCULAR MELANOMA AND CNAO MACHINE

Eye-tumours

Radiation treatment for ocular tumours such as uveal melanoma is carried out worldwide mostly using passively scattered proton beams, with a high survival rate (99%) [1]. The treatment plan typically consists of a small anterior field, with a prescribed dose around 52-60 Gy (RBE) delivered in 4-5 consecutive days. Prior to the treatment, surgical tantalum clips are implanted in the patient eye for accurate tumour definition and localization. During the irradiation, the patient is sitting on a treatment chair and asked to stably look at a pre-defined fixation point in order to spare the dose to normal tissues (optic disk and nerve, fovea, cornea, lens) and guarantee the correct alignment of the target volume with respect to the beam. This implies that the dose delivery time should be as short as possible (ideally, less than 1 minute). Passively scattered proton beams, finally collimated by a custom brass aperture close to the patient, are usually delivered by high-current cyclotrons; for example, a few hundreds of Italian patients have been treated since 2003 within the CATANA project in Catania [2] and even more at the dedicated facility in Nice, France [3].

CNAO Machine

CNAO is the unique Italian facility treating cancer patients using high-energy protons and carbon ions. Ion beams are accelerated by a 77 m synchrotron that delivers dose by an active method with two beam scanning magnets and active energy variation. Since 2011, more than 1000 patients affected from several kinds of radioresistant tumours in head&neck, abdominal and pelvic regions have been treated. CNAO proton beams are also suitable to treat ocular melanoma patients (energy range 62-90 MeV), although pencil beam scanning is the only available delivery modality and no dedicated ocular beamline is provided. In this case, a range shifter and individualized aperture are needed to make the spread-out-Bragg-peak more superficial and minimize the lateral beam penumbra, respectively. However the key issue of short irradiation time makes the standard machine settings unsuitable, because they would lead to a very long beam duration (up to 10-15 minutes). Therefore, a great effort has been made to increase the beam current in order to shorten the irradiation time as much as possible: R&D has been carried out on the different sub-systems of the machine and on its settings for an eye-dedicated machine set-up. This allowed to treat so far more than twenty patients affected by ocular melanoma since August 2016. The strategy to increase the current was twofold: increasing the number of particles extracted per cycle ("*charge increase*") and reducing the time between two consecutive extractions ("*cycle shortening*").

CHARGE INCREASE

The transmission of the proton beam through the different parts of the accelerator is affected by several beam losses that have two different effects: they obviously limit the charge arriving in the treatment room but they also strongly influence some characteristics of the beam at isocenter like the transverse foci, intensity ripple of the extracted beam and so on. For example the losses during the acceleration process reduce beam emittance of the accelerated beam and then affect the beam shape at the isocenter. In order to increase the charge quantity at the isocenter it was decided to work on two aspects: improving acceleration efficiency and improving extraction efficiency.

Increase of Acceleration Efficiency

CNAO synchrotron works injecting about 3E10 protons at 7 MeV with a multi-turn injection: the whole machine is filled with an unbunched beam; after that the RF cavity is switched on adiabatically to trap the beam in a bucket that is then accelerated to the extraction energy. At the injection energy, the space charge represents a problem for the storing and the acceleration of the beam. Indeed space charge causes a tune shift and a tune shift spread so that the beam occupies a large part of the transverse tune diagram crossing resonances even if the machine tune is stable. This situation gets worse switching on the RF cavity for trapping: the longitudinal synchrotron motion causes an oscillation of the particles in the tune diagram across resonance lines [4]. Figure 1 shows the beam current in the ring after injection, changing the injected charge by a grid inserted in the injector that decreases the number of particles without changing the emittance (Deg 100 means full beam, Deg 50 means 50% of the beam and so on). To understand the phenomenon, the number of particles is normalized to particles at the beginning: the dependence of the time decay of the beam current from the initial number of particles is evident.

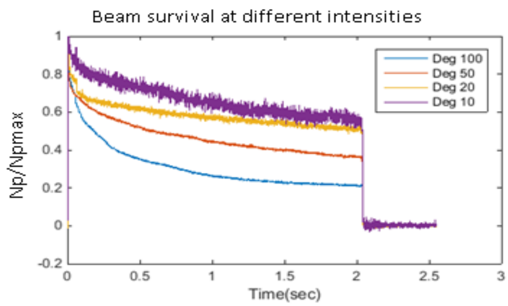

Figure 1: Beam current in the ring at different intensities: the current is normalized to its maximum value.

Figure 2 shows the influence of the RF cavity on beam current intensity: it compares the trend of the beam current in the ring after injection without RF (blue line), when RF traps beam and keeps it in the bucket (red line), when RF accelerates beam after trapping (yellow line). As in Fig. 1, the particles are normalized to the injected value.

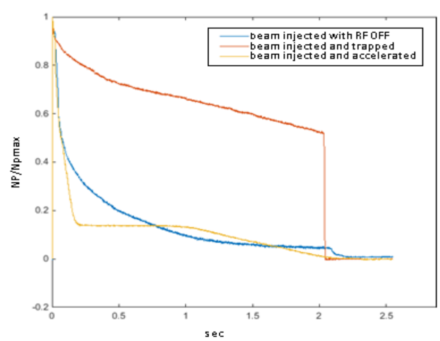

Figure 2: Influence of RF on beam survival: the current is normalized to its maximum value.

The only solution in this case is to check beam stability in different regions of the tune diagram.

The horizontal injection tune (Q_{x_inj}=1.700) has been changed with a ΔQ in the range (-0.05, 0.05) while the vertical injection tune (Q_{y_inj}=1.781) has been changed with a ΔQ in the range (-0.1, 0.05).

Figure 3 shows acceleration efficiency and particle accelerated at different tune values: improvements can be obtained with a vertical ΔQ_y=-0.05 and a horizontal detune of ΔQ_x=-0.01.

In order to increase the accelerated particles even more it was tried to detune the machine at the extraction. At extraction there are more constraints during the machine detuning because the horizontal tune is a fundamental parameter for the extraction mechanism itself.

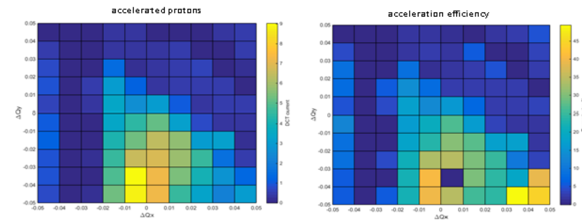

Figure 3: Accelerated particles and acceleration efficiency for different detune values at injection.

Therefore at extraction, a vertical detune was studied in the range (-0.1, 0.1) while for the horizontal tune the scan was just in the range (-0.005, 0.02). Concluding it was possible to triple the accelerated particles just detuning injection of (-0.01,-0.05) and detuning extraction of (0.000, -0.05).

Increase of Extraction Efficiency

Changing the injection and extraction tunes the accelerated particles are tripled, but with these new settings only a little part of the accelerated particles is delivered at the isocenter: the new tune settings have worsened the extraction efficiency. CNAO extraction is a resonant slow extraction: the resonance is fed by a sextupole and a betatron core drives the beam into the resonance. When a particle reaches the resonance an electrostatic septum (ESE) gives a kick and a magnetic septum (MSE) brings it out of the ring [5]. To better understand extraction mechanism the Steinbach diagram is illustrated in Fig. 4: beam exits from the synchrotron when it passes the “V line” of the resonance.

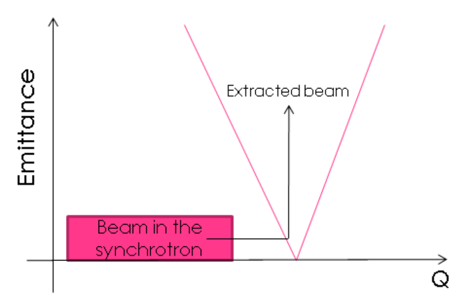

Figure 4: Steinbach diagram for extraction at CNAO: beam is driven into the resonance by a betatron core.

The measure of the time between the start of the betatron ramp and the time at which the beam is extracted from the synchrotron (the extraction time) gives useful information about machine optics since it is related to chromaticity, horizontal machine tune, beam emittance, dispersion and acceleration energy. The extraction time can be measured in two ways: from the trend of the current in the ring during extraction (DCT time) and from the time when the beam arrives at the isocenter (isocenter time). We used the extraction time to compare rapidly the horizontal tunes of different machine settings. Two phenomena were discovered: the calculated horizontal tune is different between the new optics and the original one (while no detune was set in the horizontal plane); furthermore, with the new optics, the tune is different if calculated by the DCT time or by the isocenter time. With the treatment settings, the tune evaluated by the DCT time and the isocenter time is 1.6680, with the new settings the tune evaluated by the DCT time is 1.6610 the tune evaluated by the isocenter time is 1.6645. Since horizontal tune and chromaticity are the same with the two settings (measured directly with a tune kicker magnet), one explanation of both phenomena is that with the new settings, because of different losses during acceleration, beam emittance at the extraction is very different: when beam approaches the resonance a great part of it gets lost in the synchrotron and it is not "captured" by the electrostatic septum and magnetic septum. This theory gave the hint for the right measurements to increase the extraction efficiency. To optimize the process with the new tune setting, the extraction efficiency was studied changing the orbit at the electrostatic septum. For each position a scan of the values of the electrostatic and the magnetic septa has been done. Figures 5 and 6 show the result of this study.

As a result, displacing beam far from electrostatic septum, changing the force of the electrostatic septum of 30% and the current of the magnetic septum of 0.1% the extraction efficiency was increased by 30% with respect to the treatment settings.

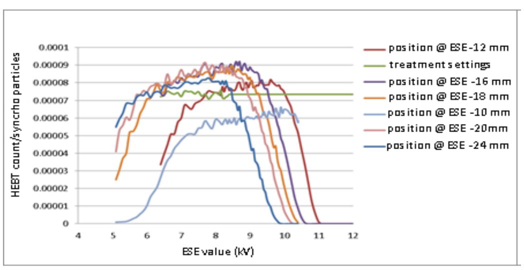

Figure 5: extraction efficiency (arbitrary units) as a function of beam position at ESE, and ESE strength.

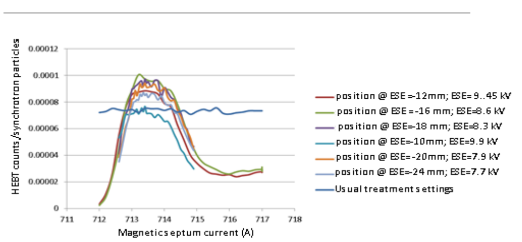

Figure 6: extraction efficiency (arbitrary units) as a function of beam position at ESE, and MSE strength.

CYCLE SHORTENING

The second strategy to increase beam intensity was to reduce as much as possible the time between two spills ("inter-spill"). For proton treatments this time is 3.8 s but it is possible to halve it for the ocular treatments reducing the acceleration time, and reducing the so called washing cycle, i.e. the cycle part in which the synchrotron magnets complete their magnetic hysteresis cycle reaching a standardization current (washing current) higher than the one used to accelerate at the maximum energy. To reduce the washing cycle it was decided to reduce the washing current and increase the current speed of the different power supplies. Changing the washing current caused a different hysteresis cycle for the magnets, modifying synchrotron optics. In order to adjust optics with the new hysteresis cycles, a current offset to the dipole power supply has been applied; this offset was obtained fitting the injection position in a highly dispersive pickup and calculating the current needed to correct it. Reducing the time for acceleration was possible implementing a system that communicates the end of the acceleration to all the devices, via the Master Timing Generator. During normal operation all the cycles had the same duration for all the energies, even though the time to accelerate the lowest energy is smaller than the time needed to accelerate the highest energy. With this new cycle structure the extraction begins as soon as the beam has reached the extraction energy and then the duration of the acceleration cycle depends on the extraction energy.

The inter-spill reduction required a firmware and hardware upgrade of several machine components, in order to improve their time performances. An example of these upgrades concerned the so called GFD, i.e. the devices that generate the reference ramp for the magnets of the ring: for each machine cycle, the GFD reads a file containing the ramp associated to the energy for the next cycle. In order to decrease the time of this file access it was needed to upgrade the GFD CPU and use the Solid state hard disk technology, in addition to a great firmware processes optimization.

CONCLUSION

CNAO machine has been optimized and re-commissioned in a restricted energy range in order to realize the first treatment of ocular melanoma with an active scanning method. Up to now more than twenty patients have been successfully treated.

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