BETATRON CORE SLOW EXTRACTION AT CNAO

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Abstract

CNAO is the only Italian hadrontherapy facility able to treat tumors with beams of protons and carbon ions.

Beam is extracted with a momentum selection scheme in which beam enters the third order resonance driven by a betatron core. When irradiating a tumor, it is thought as divided in the longitudinal plane in several slices while each slice is divided in the transverse plane in several spot called voxels. Considering the dose uniformity that can be obtained during extraction, the machine must extract an average intensity related to the voxel that requires the lower dose. A technique is needed to decrease the extracted beam intensity with respect to the nominal one. The paper shows the so called "dynamic betatron" method, that is the method adopted by CNAO some years after the first treatment to guarantee the correct average intensity according to the treatment planning requirements.

BEAM EXTRACTION AT CNAO

Beam extraction is one of the most important tasks for a clinical machine because it strongly influences the characteristics of the "spill" i.e. the beam arriving to the patient. CNAO facility is based on a synchrotron able to accelerate proton in the range 60-250 MeV/u and carbon ions in the range 120-400 MeV/u. Ion beams are accelerated by a 77 m synchrotron from which beam is extracted towards 3 treatment rooms. To fulfil the requirements on the dose homogeneity, the extraction must be a "slow extraction", i.e. in the order of seconds. The slow extraction scheme adopted at CNAO is the so called «Momentum selection moving beam» scheme. The machine tune at extraction is set near the third integer resonance ($\sim 5/3$) and the horizontal chromaticity is quite large (~ -4.0). The synchrotron optics is characterized by two superperiods for the betatron functions and two closed dispersion bumps. Dispersion is about 9 m in two opposite sides of the machine. Beam is accelerated with an average momentum spread of about $-3 \cdot 10^{-3}$ that allows to have a stable beam (thanks to the large chromaticity) even if the machine tune is near a resonance. A sextupole magnet creates an unstable region in the momentum-amplitude space (amplitude is proportional to the square root of the horizontal emittance). We can represent beam in a so called Steinbach diagram [1] (see Figure 1). During the extraction, the V-shaped unstable region is fixed (the lattice parameters are kept constant) while an acceleration mechanism is needed to move beam into the region.

An advantage of this scheme is that the extraction takes place in a wide range of emittances and this effect smoothes the extracted beam. The stacking beam must have a large momentum spread and a flattened momentum distribution.
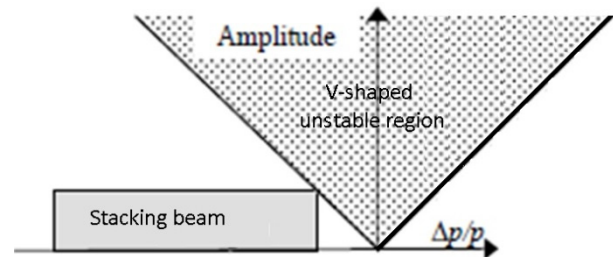

Figure 1: Steinbach diagram for «Momentum selection moving beam» scheme.

To shape the momentum distribution after the acceleration, the so called RF jump gym is performed: 180° are added to the phase of the RF cavity voltage in order to distribute the beam along the longitudinal separatrix for some hundreds microseconds. When the momentum distribution is enough constant and large, RF cavity is switched off and the beam becomes a coasting beam ready for the extraction.

The high energy beam transfer line (the so called HEBT line) [2] used to transfer beam to the treatments rooms is equipped with 4 fast magnets (the HEBT chopper) able to stop beam on a dump in 200μsec.

The irradiation of the tumor is performed dividing the target in slices along the beam directions (each slice corresponds to a different energy of the extracted beam). Each slice is divided in the transverse plane in several spots called voxels.

The dose delivery system is active: two ionization chambers ("the nozzle") [3] measure in real time the position and the number of particles delivered to the patient. Using this measurement, the beam is moved in the two transverse directions by two scanning magnets that are positioned at the end of each treatment line. When the slice has received the right dose, the nozzle switches off the HEBT chopper.

Since the time to stop the beam is not zero, some particles will arrive to the patient after the nozzle has decided that the irradiation has finished; to minimize this overdose it is important that the average extracted current is related to the total current required by the voxel so it is needed to find a way to extract cycle per cycle a different fraction of the nominal current.

CNAO BETATRON CORE

At CNAO the device that accelerates beam into the resonance gap is a betatron core. It consists in a toroidal magnet placed around the beam orbit with a diameter of

about 1.6 m and a length of about 1.5 m. Inside the magnet there are two coils; a variable current in the coils creates a variable flux of magnetic field (as shown in Figure 2) resulting in a DC voltage (hereafter indicated as V or FEM) along the beam path.
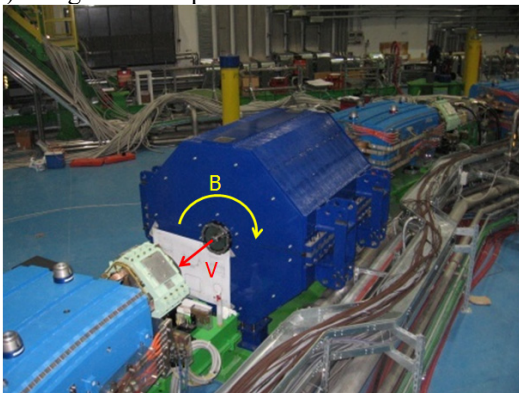

Figure 2: Betatron Core installed along the line of the synchrotron: the magnetic flux variation creates a longitudinal accelerating voltage.

A sensing coil inside the magnet gives a feedback signal used to control the bipolar power supply that drives the coils, obtaining the needed accelerating voltage. Figure 3 shows the typical current ramp needed to extract beam in 1.5 sec; the shape of the current is due to the nonlinear magnetic properties of the betatron core.
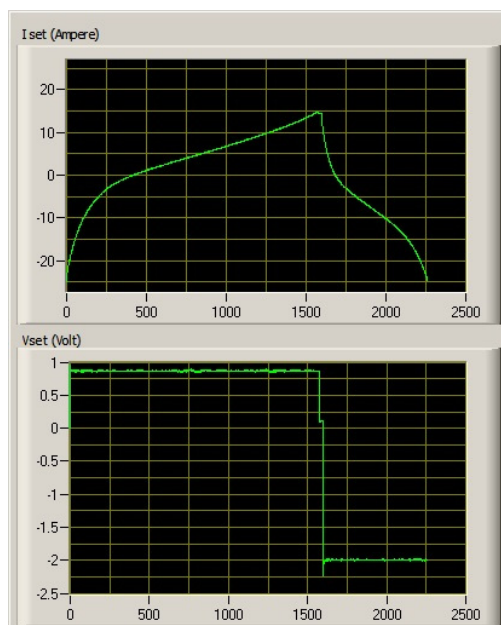

Figure 3: Current and voltage ramp to obtain a FEM of 0.86 V for about 1.5 sec.

When betatron core is on, every turn each particle receives an energy kick (ΔE) that is given by where Z is the atomic number, A is the mass number and V is the voltage induced through the betatron core.

$$\Delta E = \frac{Z}{A} V \qquad (1)$$

As it was said in the previous section, beam is prepared for extraction, shaping in a proper way its momentum spread distribution, so the betatron force must be related to the momentum spread of the particles by the following formula:

$$\frac{\Delta p}{p} = \frac{1}{\beta^2 E} \frac{Z}{A} V F \Delta T \qquad (2)$$

where $\frac{\Delta p}{p}$ is the particle momentum spread with respect to the resonant momentum spread, β is the standard relativistic factor, E is the total relativistic energy per nucleon, F is the particle revolution frequency and ΔT is the time required for the extraction. Eq.(2) is obtained from Eq. (1) using the standard relativistic relation between energy and momentum and considering that $F\Delta T$ is the number of turns before extraction and hence the number of energy kicks received by the betatron. Obviously the revolution frequency, the betatron factor and the beam energy change during extraction because of the betatron acceleration but Eq.(2) is a good approximation of the real formula using the starting value for all the energy dependent quantities. Eq.(2) does not take into account other acceleration sources during extraction. At CNAO, RF cavity is switched on during extraction performing the so called Empty Sweeping Bucket [4], i.e. an empty bucket outside the beam that changes its energy at a high frequency: beam moves in the longitudinal phase space along the RF cavity lines of force. As a consequence, Eq. (2) is not usable to calculate directly the betatron force for all the energies of proton and carbon beams because it does not contains the contribution of the RF cavity voltage. The Empty Sweeping Bucket allows to reduce the spill ripple and contributes to beam extraction. If RF cavity parameters are not correctly set, the RF bucket contributes too much to the beam extraction and furthermore causes beam losses during the process. However, if the parameters of the Empty sweeping bucket are set correctly, the proportionality between the extraction time and the betatron voltage given by Eq. (2) is maintained. Figure 4 shows a carbon beam energy extracted with different betatron voltages, while Figure 5 shows the linear proportionality between the betatron voltage and the extracted beam intensity in the same case: this linearity is fundamental for the principle of the Dynamic Betatron method illustrated in the next section.
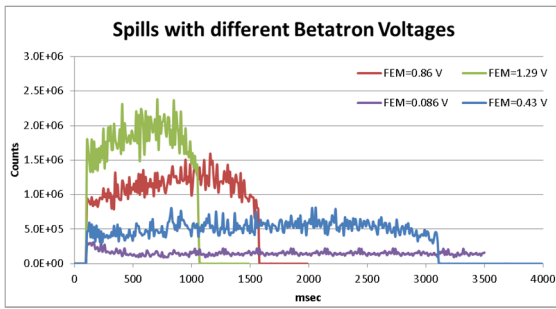
Figure 4: Spill structure with different betatron voltages. 3.5 sec is the maximum extraction time.
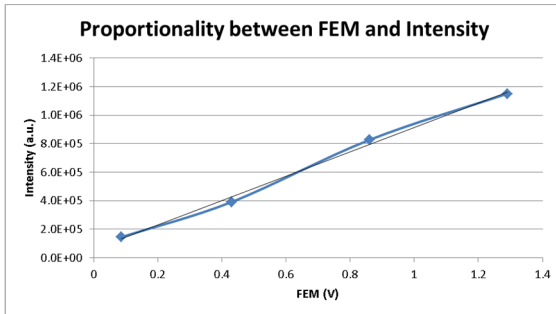

Figure 5: Relationship between betatron voltage and extracted beam intensity.

DYNAMIC BETATRON METHOD

A way to regulate beam intensity as a function of the voxel requirements is to decrease beam intensity by the use of degraders, i.e. mechanical filters with different transparency factors. This idea has been implemented at CNAO and was exploited for some years during the treatments by using three degraders [5] with a transparency factor of 10%, 20% and 50% installed in the medium Energy beam line MEBT (where beam has the energy of 7 MeV/u) before being injected in the synchrotron. This method has some disadvantages:

- The degraders are moved cycle per cycle (about every 3 sec), so the moving system needs an accurate maintenance in order to prevent failures during the treatment.
- The movement of the degraders needs about 1 sec and this time lengthens the time between two spills.
- Since at the injection energy the space charge tune shifts are relevant [6], reducing the injected charge in the synchrotron changes the space charge effects that influence beam losses. Different losses during injection and acceleration lead to different emittances and then different beam characteristics of the extracted beam (energy and foci): optics must be set with great care in order to reduce these effects.
- To guarantee that the extracted current has the right value the nominal current must be stable enough, and this is not always true in particular after maintenances on the sources or the LINAC.
- Only 4 different reduction factors can be obtained.

The dynamic betatron method has allowed eliminating the use of the degraders and all the related disadvantages. The principle is to change the betatron voltage cycle per cycle as a function of the accelerated current. At each cycle the betatron voltage is calculated according to the formula:

$$V = \frac{N}{N_{max}} V_{max} R \qquad (3)$$

Where V_{max} is the betatron voltage at the nominal accelerated current, N is the current accelerated in the cycle, N_{max} is the nominal accelerated current and R is the fraction of the nominal extracted current required by the slice.

This strategy has a further important advantage: using the dynamic betatron instead of a degrader it is possible to reduce the number of acceleration cycles to irradiate the same slice. Indeed a degrader reduces the injected current in the ring while with the dynamic betatron method the accelerated current is always the same. This results in a reduction in the treatment times that depends on the treatment characteristics and on the stability of the accelerated current. The comparison of 50 treatments with degraders and with dynamic betatron showed a time reduction of about 30%.

This is an important aspect since the time length of a treatment is one the main issues of a clinical machine [7].

CONCLUSION

An efficient way to regulate the extracted beam intensity has been found using a cycle per cycle regulation of the betatron core voltage used for the slow extraction at CNAO. This method has several advantages with respect to a regulation of the injection current obtained by mechanical filters.

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