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EMPTY SWEEPING BUCKET FOR SLOW EXTRACTION

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Abstract

The extraction process is one of the most important aspects of a clinical machine because it defines the quality of the dose delivered to the patient. In particular, the quality of the extracted beam is strongly affected by the stability of the power supplies whose current ripple creates a ripple in the intensity of the extracted beam. When it is not possible to improve power supply stability, it is needed to apply some additional techniques in order to cure spill ripple. Empty Sweeping Bucket is an RF gym that improves the Empty Bucket Channelling technique by using an energy-moving bucket instead of a stationary one. The paper shows the advantage and the efficacy of such a technique applied to improve the quality of the spill at CNAO, the Italian hadrontherapy facility.

CNAO DOSE DELIVERY SYSTEM

CNAO is the unique Italian facility treating cancer patients using both high-energy protons and carbon ions. Ion beams are accelerated by a 77 m synchrotron and the beam is extracted into 3 treatment rooms. The beam extraction technique is the so called «Momentum selection moving beam»[1]: the beam has a large momentum spread and a small emittance. A betatron core slowly (i.e. in more than 1 sec) accelerates the beam to drive it into the third order resonance gap created by a sextupole magnet. The advantages of this scheme are that lattice parameters are constant during the process and extraction takes place in a large range of emittances. This behavior smoothed the extracted beam (the so called "spill").

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

The dose is delivered to the patient by an active system: at the end of each treatment line two ionization chambers (the so called Nozzle) [3] measure in real time the position and the number of particles delivered to the patient. The nozzle guarantees that each part of the tumour is irradiated by the right dose: it controls the current of two scanning magnets that move the beam in the two transverse directions and it switches on and off the HEBT chopper to let the beam arrive or does not arrive in the treatment room.

SPILL QUALITY

Spill quality is one of the main issues of a medical machine because it determines the quality of the treatment. The great advantage of the hadrontherapy with respect to the traditional radiotherapy is the possibility to irradiate only the cancer cells preserving the healthy cells thanks to the Bragg peak properties. However, this is true only if the dose delivery system is able to control position and quantity of the delivered dose. This goal can be obtained only if the beam coming from the synchrotron has a good "quality", i.e. it has an almost uniform intensity versus time. Because of the current ripple of the synchrotron power supplies, the beam is not extracted uniformly, the machine tune is not constant and then the resonance gap is not fixed and moves at a high frequency: power supplies ripple is turned into spill ripple. Measuring and improving spill quality appears as a fundamental commissioning activity.

Figure 1 and 2 show respectively the time profile and the frequency spectrum of a spill just extracted after acceleration. Several spectral components are evident in particular the 1.2 kHz coming from the main dipole power supply.

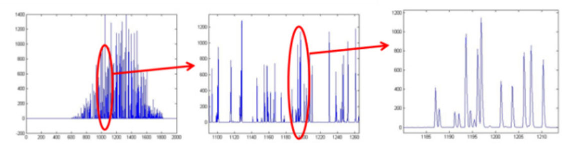

Figure 1: Time profile (the x axis is in msec) of the spill extracted after acceleration.

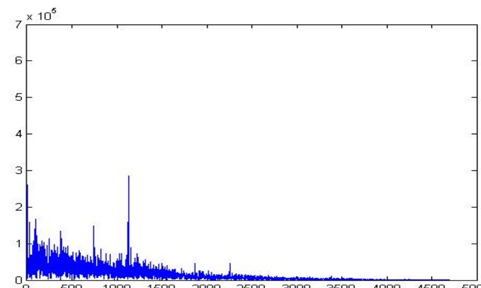

Figure 2: Frequency spectrum (the x axis is in Hz) of the spill extracted after acceleration.

Spill quality can be measured using three parameters: spill *max duty factor*, spill *rms duty factor*, spill displacement. *Max duty factor* is simply defined as the maximum count over the average value of all the counts. *Rms duty factor* is defined as

$$\frac{\left(\sum_{i=1}^{N} C_i\right)^2}{N\sum_{i=1}^{N} C_i^2} \quad (1)$$

where C_i is the i-th count and N is the total number of counts. Spill displacement is the displacement in the horizontal and vertical plane of the spill measured at the isocenter.

To evaluate *max* and *rms duty factor*, it is needed to acquire the spill current at a high rate (about 10 kHz) while for the spill displacement a 1 kHz acquisition is needed. As shown in Fig 3. these three quantities are correlated but there are important differences among them.

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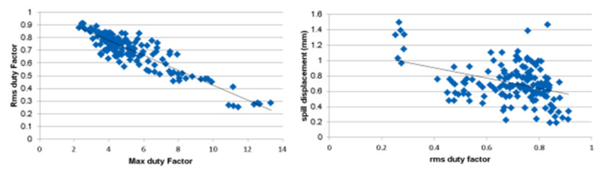

Figure 3: Example of correlation between the three spill quality parameters.

The *rms duty factor* is the most effective parameter to be used when trying to optimize spill quality. *Max duty factor* is strongly affected by normal statistic variations because it uses the highest count during the spill. *Spill displacement* depends on the line optics so the same extracted spill has a different displacements with different settings of the line quadrupole magnets.

EMPTY BUCKET CHANNELLING

A standard way to smooth spill ripple is the Empty Bucket Channelling [4]. The empty bucket channeling idea is to create an empty bucket at a frequency far from the one of the circulating beam. This can be obtained by the same RF cavity used for acceleration. Creating an empty bucket the particles are forced to move in the small phase interval between the bucket separatrices: in this way the speed crossing the resonances increases. The extracted particle intensity is given by:

$$\frac{dN}{dt} = \frac{dN}{dQ}\frac{dQ}{dt} \tag{2}$$

Where the relative motion between the beam and resonance $\frac{dQ}{dt}$ is be the sum of a constant velocity $\dot{Q}_0$ and a ripple term $\dot{Q}_r$:

$$\frac{dQ}{dt} = \dot{Q}_0 + \dot{Q}_r = \dot{Q}_0\left(1 + \frac{\dot{Q}_r}{\dot{Q}_0}\right) \tag{3}$$

The presence of the empty bucket increases $\dot{Q}_0$, decreasing the influence of $\dot{Q}_r$.
The beam energy engaged by the resonance must be smaller than the bucket half height, so the higher is the voltage the greater are the improvements on the spill. Furthermore, to optimize the effect the bucket must be properly positioned with respect to the resonance [1].
At CNAO this technique was used in the first two years of treatments. Figure 4 shows the improvements of the empty bucket channelling on the spill quality.

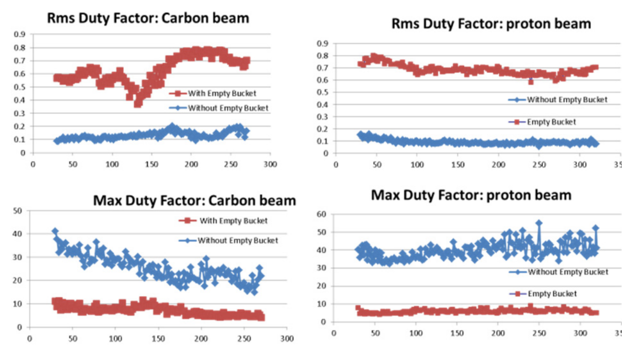

Figure 4: improvements of the empty bucket channelling on the spill quality.

EMPTY SWEEPING BUCKET

The Empty sweeping bucket consists essentially in creating an empty bucket that is not stationary but moves in energy at a high frequency. This technique, used at CNAO since 2014, is more efficient in smoothing spill with respect to the empty bucket channelling, allowing to reduce the beam losses during the extraction. There are 6 parameters that must be adjusted:

1. Way of changing the frequency;
2. Bucket Voltage;
3. DeltaFBucket: Frequency of the Bucket with respect to the acceleration energy;
4. DeltaFSweep: Frequency gap during the sweep;
5. Sweep period;
6. Beam position in a dispersive pick-up (9 m dispersion point) at the end of acceleration.

Figure 5 shows the ways of changing bucket frequency that have been tested.

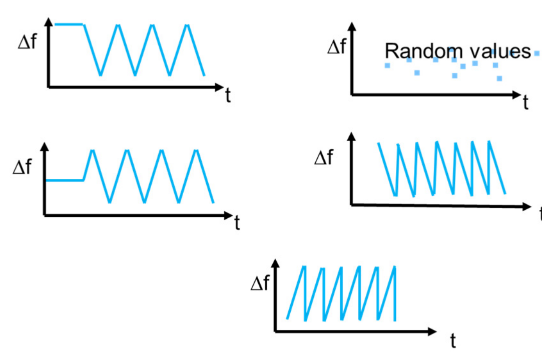

Figure 5: Tested schemes to change the Bucket frequency.

For each scheme it was possible to obtain the same results just choosing in a suitable way the other 5 parameters. The physical effect of these parameters is to change the position of the bucket with respect to the the third order resonance gap and to the beam. The sweep period has been set at 100 µsec (equal to the spill sampling frequency) while the other parameters have been changed for each energy. It is possible to optimize the Empty S-Bucket parameters also if DeltaFBucket=DeltaFSweep; this eliminated a degree of freedom in the research of the best set-up. For each energy:

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- 6 values of voltages have been tested.
- For each voltage the DeltaFBucket has been changed in the range: 3kHz-20kHz.
- For each DeltaFBucket value, the beam position before extraction has been changed from -35mm to -20mm.

In Fig. 6 each point series indicates a combination of parameters with the fixed bucket voltage that allow having transmission efficiency greater than 40% and a spill max duty factor smaller than 4.5.

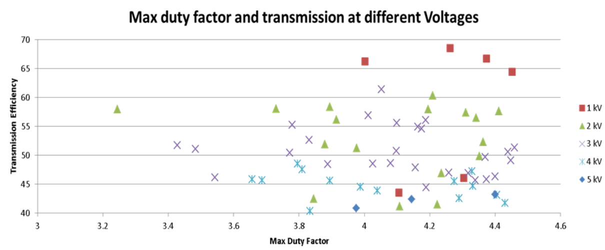

Figure 6: Max duty factor and transmission at different Voltages.

We have no points for 6 kV while the voltage at which we have the greatest number of points is 3 kV. This means that while with the empty bucket channelling technique the greater is the voltage the better is spill quality (the limit is the maximum allowed voltage, which is 6 kV for CNAO cavity), with the empty sweeping bucket the best results are obtained with small voltages. Figure 7 shows the comparison between the Empty Bucket and the Empty Sweeping Bucket on the spill quality parameters.

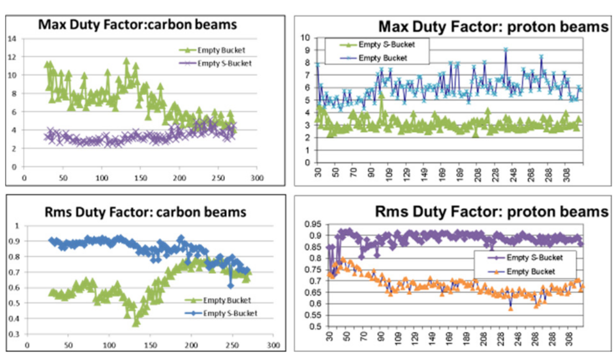

Figure 7: comparison between the Empty Bucket and the Empty Sweeping Bucket on the spill quality parameters for Proton beams and Carbon beams.

Figure 8 shows the frequency spectrum without any bucket, with the Empty Bucket channeling and with the Empty Sweeping Bucket.

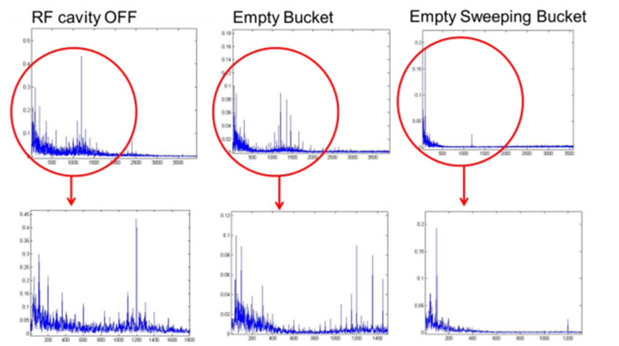

Figure 8: On the top, Frequency spectrum with RF cavity OFF, with Empty Bucket and with Sweeping Bucket. On the bottom, the zoom graphs in the three cases.

CONCLUSION

In a clinical machine, spill quality is a fundamental aspect to be taken into account. At CNAO an efficient strategy has been elaborated to improve the spill quality in the framework of a betatron core slow extraction. The adopted method exploits the same hardware used for beam acceleration and it is an evolution of the more known empty bucket channelling.

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