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DESIGN AND COMMISSIONING OF THE RF-KO EXTRACTION AT CNAO

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Abstract

CNAO is one the six hadrontherapy centres all around the world that produce both proton and carbon ions beams. It is based on a synchrotron in which the beams are extracted by a slow extraction mechanism that uses a betatron core. In the last years an electrostatic exciter has been installed along the ring in order to allow beam extraction using the RF-KO method. The system has been commissioned and allows extraction according to the clinical beam parameters. The paper illustrates how the RF-KO method has been implemented in CNAO under the hardware and software point of view. The characteristics of the proton and carbon beams will be also presented.

INTRODUCTION

The National Centre for Oncological Hadrontherapy (CNAO) in Pavia is one of the six centres worldwide that provides clinical treatments for oncological pathologies with both proton and carbon ions beams. The beam particles are accelerated by a 25 m diameter synchrotron up to 400 MeV/u for carbon ions and up to 250 MeV for protons [1].

In order to measure and control the radiation doses delivered to the patients, it is necessary to extract the beam slowly over periods of the order of a few seconds. To aim this, a third order resonance excited by a sextupolar field can be used. Once created the triangular stable region, particles must be brought out of it in a controlled way in order to amplify their betatron oscillations till they reach the extraction septum.

The resonant tune chosen for the extraction at CNAO is $Q_x = 5/3$ and currently the beams are extracted by means of a betatron core that accelerates the particles toward the unstable region. Right before the extraction begins, the phase of the RF cavity voltage is changed by 180° to flatten the beam momentum spread and then turned off to de-bunch the beam.

Once all the dose prescribed by the treatment plan for a particular energy is delivered, the remaining beam circulating in the accelerator can't be reaccelerated to the next higher energy because before acceleration it would be necessary to re-bunch beam causing lots of beam losses. To implement the so-called multi-energy extraction, in which the unused beam is reaccelerated to continue the treatment at a higher depth in the tumor volume, an extraction technique that doesn't need the de-bunching of the beam is required.

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RF-KO EXTRACTION TECHNIQUE

In the last years CNAO has worked on the implementation and optimization of RF-KO (Radio-Frequency Knock Out) as an alternative to betatron core extraction. In RF-KO extraction, the beam is conducted into the unstable region by increasing the amplitude of the betatron oscillation by means of a horizontal exciter.

So that the perturbations are resonant, the frequency of the RF signal must match the horizontal betatron frequency:

$$f_{RFKO} = (n \pm q_x) f_{rev} \qquad n \in \mathbb{N}$$

where q_x is the fractional part of the horizontal tune and f_{rev} is the revolution frequency. Due to the particle momentum spread, both the revolution frequency and the tune are not unique and so a sweep in RF frequency is needed to guarantee the correct match for all the particles. At first order in $\frac{dp}{p}$, the RF frequency can be written as:

$$f_{RFKO} \approx f_0 \left[(n \pm q_0) + \frac{dp}{p} \big(\xi + \eta (n \pm q_0) \big) \right] \quad n \in \mathbb{N}$$

where f_0 and q_0 are respectively the revolution frequency and the fractional part of the horizontal tune of the synchronous particle, ξ is the chromaticity and η is the slippage factor.

However, the frequency modulation (FM) alone is not sufficient to guarantee a good quality of the temporal structure of the extracted beam (called *spill*) with uniform distribution of extracted particles over time. Since not all the particles have the same amplitude of betatron oscillations, the power required to excite them into the resonance is function of the amplitude itself; in order to keep the intensity of the extracted beam uniform over time, also an amplitude modulation (AM) is necessary. Considering the impossibility of guaranteeing perfect repeatability between one spill and another, for example due to the current ripples of the power supplies or the variability of the number of accelerated particles, a purely analytical approach to the shape of the voltage ramp may not be very effective. For such reasons a feedback system has been implemented to adjust the amplitude of the RF signal according to extraction status.

Nevertheless, a voltage analytical function is needed to have a starting point for the feedback. The chosen function is a simplified versions of the one used at HIMAC and presented in [2] which reproduces the same trend despite a greater practicality from the computational point of view:

$$V(t) = -\frac{a_1}{\sqrt{f_{rev} \cdot t}\,[a_2 + \ln(1 + a_2) + \ln(t/\tau_{extr})]} \qquad (1)$$

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where f_{rev} is the revolution frequency of the beam, τ_{extr} is the desired duration of the extraction and a_1 and a_2 are two parameters that allow you to adjust the maximum value and the curvature of the voltage ramp.

RF-KO IMPLEMENTATION

Hardware Description

The horizontal perturbations needed to amplify the particles betatron oscillations are given by the radiofrequency fields generated in an electrostatic kicker. The deflection angle due to the electric field is computed as:

$$\theta_x = \tan^{-1}\left(\frac{|V_x|}{d} \cdot \frac{l_{eff}}{p \cdot \beta}\right)$$

where $|V_x|/d$ is the electric field at kicker plates, l_{eff} is the effective length of the kicker and p and β are the momentum and the relativistic Lorentz factor of the beam respectively. The system is composed by a Low-Level RF (LLRF) board identical to the one used for beam acceleration, a 500 W RF amplifier, a voltage divider for the voltage feedback loop and a RF balun. With a kicker length of 37 cm, a gap of 137.24 mm between the electrodes, the maximum deflection for the highest carbon ion energy (400 MeV/u) is 0.8 µrad [3].

Software Description

For its functioning, the RF-KO system must be interfaced with many other systems. A schematic of these interactions is illustrated in Fig. 1.

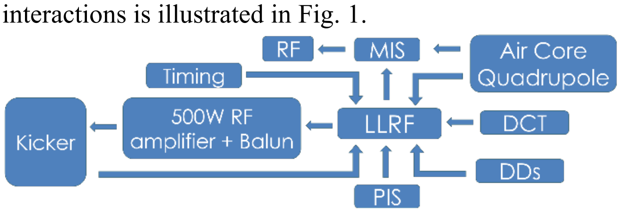

Figure 1: Schematic architecture of RF-KO system.

All temporal triggers, combined with the information needed for the correct generation of the beam required by the treatment plan, are delivered to the LLRF by the Timing system. Once received the trigger event for the RF signal generation and the amount of charge accelerated in the ring measured by a DC Current Transformer (DCT), the LLRF computes the reference voltage ramp given in Eq. (1) and sends the signal to the RF amplifier imposing for the extraction time:

$$\tau_{extr} = \frac{DCT \cdot Eff_{extr}}{I_{des}}$$

where Eff_{extr} is the extraction efficiency for a given particle and energy and I_{des} is the desired extraction intensity.

To guarantee a uniform intensity of the extracted beam, every 10 µs the LLRF receives from the Dose Delivery System (DDs) the counts registered by two ionization chambers. Combining them with the readout voltage of the kicker, every 1 ms a PI controller computes the corrections to apply to the reference voltage ramp.

In order to control the spill non-uniformities at a scale of 100 µs, second feedback has been implemented to minimize the variations on the derivative of the counts measured by the DDs. This feedback controls the current of the Air Core Quadrupole, a special iron-free magnet that can provide small but very fast corrections to the machine tune.

As can be seen in Fig. 1, the RF-KO interacts also with two security systems: the Machine Interlock System (MIS) and the Patient Interlock System (PIS):

- The role of the MIS is to send to the LLRF of the RF cavity the signal to destroy the beam circulating in the synchrotron when situations in which the beam may have not clinical characteristics occurs. With the implementation of RF-KO the MIS checks that the counts of the two DDs chambers, replicated by the LLRF, are compatible and that the Air Core Quadrupole power supply is working properly.
- The PIS is the system that manages the High Energy Beam Transfer line chopper, a group of four fast magnets able to stop beam on a dump in 200 µs. Since the DDs registers no counts when the chopper stops the beam, the two feedback would react increasing the kicker voltage and changing the machine tune to favour the extraction. If this were allowed, the intensity of the extracted beam would grow very rapidly and the charge in the ring would be exhausted in a very short time. For these reasons the LLRF interacts with the PIS to turn off the loop ad pause the extraction according to the chopper status.

Results of the Commissioning

The aim of the commissioning strategy was to achieve an extraction of both proton and carbon ions beam of at least the same quality of that obtained with betatron core. The main aspects taken into account were:

- The beam extraction efficiency.
- The spill intensity uniformity at temporal scales from 100 µs up to 10 ms.
- The beam average intensity.
- The accuracy of the extraction energies.

Once all these requirements were met, the optics of the transfer lines were optimized to obtain beam size at the isocenter compatible with the clinical specifications and a correct beam centering.

The implementation of RF-KO required the studies and optimization of many parameters with respect to betatron core. In particular:

- The voltage of the RF cavity has been to decrease as much as possible the beam momentum spread. In fact, unlike the betatron core extraction, the beam extracted with RF-KO has the same momentum spread of the beam circulating in the accelerator.
- A reduced tune spread is also preferable; therefore, the chromaticity must be brought toward zero. Best results were obtained with $\xi_x = -0.58$.

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- The machine horizontal tune has a great impact: a beam far from the resonance is stable but difficult to extract, on the other hand if the beam is too close to the resonance there may be losses when the resonance sextupole is turned on. Thus, the synchrotron quadrupole's setpoints were set to avoid losses and, at the same time, not to hinder extraction too much.
- The beam position and divergence at the electrostatic septum strongly affects the extraction, so the horizontal synchrotron correctors were used to create a bump in the beam orbit at the septum.
- The frequency of the kicker RF signal and the parameters for the two PI feedback.

Considering the fact that the dose required to treat cancer changes voxel by voxel, the extracted beam intensity can be modulated with respect to a nominal value via a reduction factor (called *degrader*). The clinical intensities values are reported in Table 1 and Table 2, while the measured ones are reported in Fig. 2. Even though the intensities obtained with RF-KO are a bit lower than the reference ones, the improvement compared to the betatron core extraction is evident.

Table 1: Clinical Intensities for Proton Beams

Degrader	RF-KO	Betatron Core
100%	4×10^9 part/s	2×10^9 part/s
50%	2×10^9 part/s	1×10^9 part/s
20%	8×10^8 part/s	4×10^8 part/s
10%	4×10^8 part/s	2×10^8 part/s

Table 2: Clinical Intensities for Carbon Ions Beams

Degrader	RF-KO	Betatron Core
100%	8×10^7 part/s	4×10^7 part/s
50%	4×10^7 part/s	4×10^7 part/s
20%	1.6×10^7 part/s	8×10^6 part/s
10%	8×10^6 part/s	4×10^6 part/s

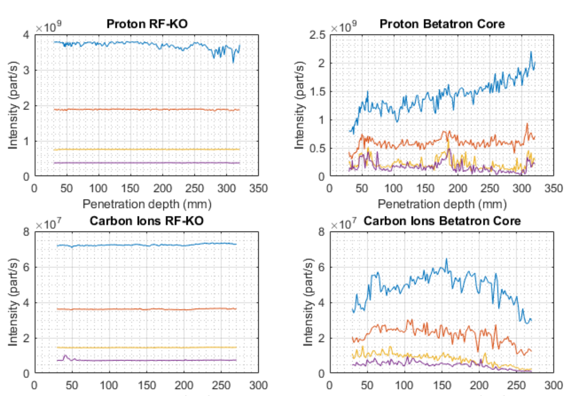

Figure 2: Measured beam intensities for the different degrader factors.

Finally, regarding the control of the ripple spill, one of the main quantities taken into account was the ratio between the maximum counts and the average counts registered by the DDs at sample rates of 10 kHz, 2 kHz and 1 kHz. As can be seen in Fig. 3 and Fig. 4, while at the highest sample rate the spill quality of the beam extracted by RF-KO and by betatron core are comparable, RF-KO strongly suppresses spill ripples at sample rates below 2 kHz.

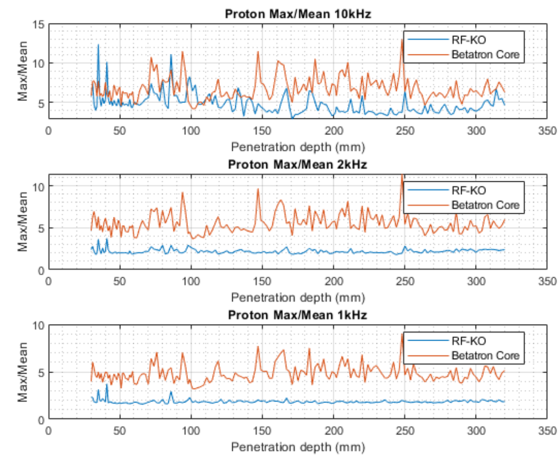

Figure 3: Comparison of proton beams spill quality.

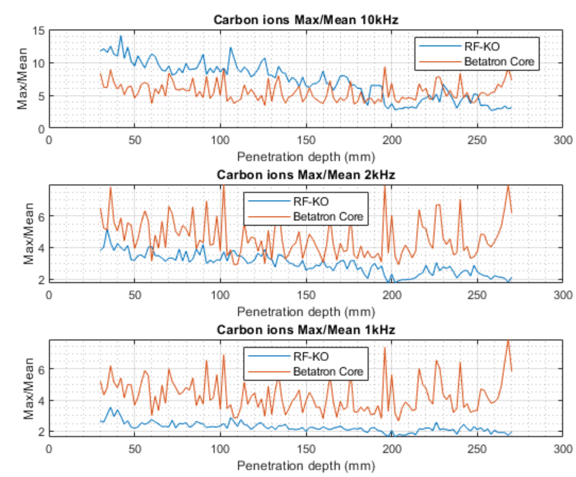

Figure 4: Comparison of carbon ions beams spill quality.

REFERENCES

[1] S. Rossi, "The National Centre for Oncological Hadrontherapy (CNAO): status and perspectives", in Physica Med., vol. 31, pp. 333-351, 2015. doi:10.1016/j.ejmp.2015.03.001

[2] T. Furukawa *et al.*, "Global spill control in RF-knockout slow-extraction", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 522, pp.196-204, 2004. doi: /10.1016/j.nima.2003.11.395

[3] S. Savazzi et al., "Implementation of RF-KO Extraction at CNAO", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 3469-3471. doi:10.18429/JACoW-IPAC2019-THPMP010