

RF-KO EXTRACTION AT CNAO FOR CLINICAL BEAMS

S. Marangoni, S. Alpegiani, E. Bressi, G. Debernardi, L. Falbo,
P. Meliga, C. Priano, G. Venchi, F. Zanoli
Fondazione CNAO, Pavia, Italy

Abstract

CNAO is one of the few hadron therapy 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 either a betatron core or an electrostatic exciter referred to as RF-KO (Radio-Frequency Knock Out). The RF-KO extraction method has been commissioned and in May 2024 we started using RF-KO for proton treatments, while in June 2025 we started using RF-KO for carbon treatments. This paper illustrates characteristics of clinical beams and the impact on patient treatment, comparing the results of the present extraction method with the betatron core one.

INTRODUCTION

The National Centre for Oncological Hadrontherapy (CNAO) in Pavia is one of the few 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]. Alongside with protons and carbon ions, CNAO can provide other ionic species: helium beams are currently under commissioning in treatment and experimental rooms [2] and other species are foreseen in the next future.

In a hadrontherapy synchrotron it is necessary to extract the beam slowly over periods of the order of a few seconds in order to deliver the dose to the patients in a controlled and measurable way. For this purpose a third order resonance excited by a sextupolar field can be used: after acceleration, beam particles are brought out of the stable region, they become unstable in the horizontal transverse phase space until they reach the electrostatic extraction septum.

CNAO was designed to extract particles by the use of a betatron core [3] that accelerates slowly the beam with a DC voltage of few volts: changing the momentum spread with a high horizontal chromaticity allows to change particles tune until they cross the resonance line of Steinbach diagram. The drawback of betatron extraction is that beam must be unbunched during extraction: this creates problem in a multiacceleration regime. Indeed in multiacceleration regimes, after the delivery of beam at a given energy, the remaining beam in the ring is accelerated to a higher energy but the trapping process to pass from coasting to bunched beams is very inefficient. Since CNAO plans to implement multiacceleration, in 2018 an electrostatic RF kicker [4] has been installed to implement RF-KO (Radio-Frequency Knock Out) that allows to extract bunched beams. In the RF-KO extraction the horizontal RF field increases the amplitude of betatron oscillations until the particles cross the Steinbach lines.

Passing from betatron to RF-KO extraction needed great changes in the synchrotron optics in addition to the implementation of strategies to use RF-KO kicker to match CNAO clinical requirements. Since 11th May 2024 proton treatments are performed by RF-KO extraction and since 21st June 2025 also carbon treatments are performed by RF-KO. This paper will summarize CNAO RF-KO characteristics, a part of which have been already presented in [5], and then it will illustrate beam calibrations and optimizations that led to treatments using RF-KO.

CNAO RF-KO DESCRIPTION

In order to have resonant perturbations with RF-KO extraction, the frequency of the RF signal must match the horizontal betatron frequency. Due to the beam momentum spread, the betatron frequency is not unique and therefore a sweep in RF-KO frequency is needed to correctly excite all the particles. In addition to FM modulation, the RF signal must be also AM modulated to match the spread in betatron amplitudes, but a purely analytical approach for the voltage ramp [5] is not sufficient to guarantee a uniform distribution of extracted particles over time.

It has been implemented a feedback system (“Voltage feedback”) on the RF-KO voltage: at a rate of 1 kHz the system reads the counts from the dose delivery system (DDS) and change the kicker voltage using a IIR filter to keep the intensity constant.

The frequency sweep amplitude is adjusted roughly to 10 kHz while the maximum frequency is firstly set to one third of the revolution frequency and then it is finely adjusted energy per energy considering extraction efficiency and the maximum power deliverable by RF-KO amplifier (500 W).

The voltage feedback guarantees a perfect control of beam extracted intensity on the time scale of the voltage feedback; however looking at the spill structure at a 10 kHz frequency a ripple appears due to the synchrotron power supplies ripple.

To smooth time spill structure an additional feedback has been implemented using an iron-free quadrupole (air-core) that can provide small but very fast corrections to the machine tune. Every 50 μ s, the air-core feedback system computes the derivative of the counts from the dose delivery and uses it to regulate air-core quadrupole current to smooth spill structure.

The implementation of voltage and air-core loops makes the measurement of particles at the dose delivery of fundamental importance for beam extraction. This aspect needed a specific study in using RFKO extraction in real treatments due to the way beam is delivered to the patients in CNAO.

The tumour irradiation is performed dividing the tumour in spots that are irradiated changing beam energy and the current of two fast kickers (scanning magnets). Figure 1 shows the CNAO HEBT (High Energy Beam Transfer) line that is made up of a first part and five lines: three horizontal lines for treatments (indicated in the figure as line Z, line T and line U), one vertical line for treatments (in the figure indicated as line V), one horizontal line for experimental irradiations (indicated in the figure as XPR line).

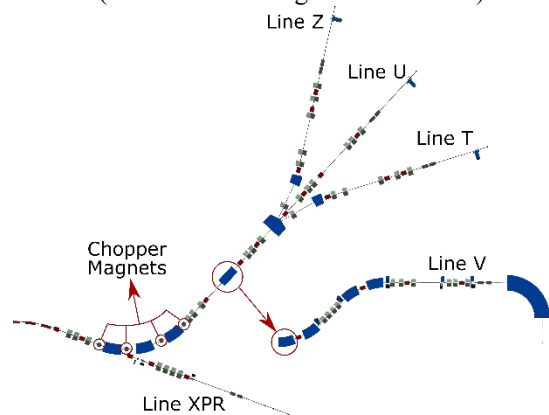


Figure 1: HEBT layout at CNAO.

The delivery of the dose is managed by the use of four fast magnets (the speed is about $3.25 \text{ A}/\mu\text{s}$ corresponding to $200 \mu\text{s}$ at the maximum current) positioned in the HEBT first part and indicated in the figure as “chopper magnets”. They can create a closed orbit bump that allows the beam to overpass a dump positioned on the trajectory created by the three dipoles among which the chopper magnets are positioned. For each energy, when the dose delivery system measures that all the needed dose at a given transverse position has been delivered, a system named PIS (Patient Interlock System) switches off the chopper magnets before the dose delivery system changes the current of the scanning magnets for the next spot. RF-KO must know that chopper has been switched off in order to avoid that the loops react in a wrong way: an extracted beam that does not arrive at the isocenter would cause a fast increase of RF-KO voltage and air-core current causing a fast beam extraction on the HEBT dump.

In other words, when chopper is switched off during beam extraction, RF-KO must “pause” its two feedbacks and manage properly voltage and air-core current. For this reason the commands that PIS sends to chopper power supplies are sent also to the RF-KO system. Several solutions have been investigated to find the best way to manage voltage and air-core current when the chopper is switched off in order to guarantee the same beam characteristics when the chopper is re-switched on. Indeed when chopper is switched off, voltage and/or air-core current could be put to zero or be kept to a constant value that can be equal or a fraction of the mean value it had a few milliseconds before extraction interruption. When the chopper is re-switched on, if voltage or air-core current were put to zero, there is the possibility to initially increase them linearly to their pre extraction interruption average values before turning on the feedbacks.

Beam behaviour has been studied in the cases obtained mixing these strategies for voltage and air core current. The best scenario was obtained in the following way: as soon as PIS switches off the chopper, voltage is put to zero and air-core current is initially increased to prevent further extraction and then sent to the average value computed in the 5 ms preceding the chopper power off. When PIS re-switches on the chopper, RF-KO awaits the time needed for the power supply to reach the correct current value depending on the energy and then increases linearly the voltage to the previous value in $250 \mu\text{s}$. After other 2.75 ms the voltage feedback is turned on. Regarding the air-core current feedback, it is reactivated immediately after the chopper current has reached its setpoint.

CARBON IONS AND PROTONS BEAM COMMISSIONING

The aim of the RF-KO commissioning was to match all the clinical requirements on the extracted beams. The extraction energy was adjusted within 0.1 mm using measurement of the Bragg peak profile with a peak finder detector. The transverse sizes at the isocenter were adjusted in order to have similar sizes in all the treatment rooms and with an asymmetry between the two transverse axis smaller than 1 mm ; the value of the FWHM (full width at half maximum) changes with the energy and it was set between 22 mm and 16 mm for protons and between 12 mm and 4 mm for carbon ions; particular attention has been dedicated to the shift of beam barycenter and FWHM during the extraction in the same spill.

For both species, RF-KO gave an extraction efficiency always higher than betatron core in particular at the highest carbon ions energy where a factor 3 has been obtained.

The nominal intensities with betatron core are $2 \cdot 10^9$ protons per second and $4 \cdot 10^7$ carbon ions per second. The nominal intensities with RF-KO were doubled and, as for betatron core, three additional intensities were commissioned: 50%, 20% and 10% than nominal one. The intensity used during a treatment depends on tumor shape: with RF-KO most of the dose is delivered with 50% intensity limiting the other intensities to few spills. As it is shown in Fig. 2, the improvement in the precision of the extraction intensity delivered is very significant comparing the betatron core and RF-KO extraction methods for both protons and carbon ions.

The spill intensity uniformity is an important aspect for a good treatment quality. It has been commissioned by a statistical analysis on the counts measured by DDS every $100 \mu\text{s}$ calculating Max/Mean (the ratio between the maximum value over the mean value of the counts) and the duty factor (the ratio between the squared mean of counts per spill and the mean of the counts squared). For each intensity RF-KO beams are a little more uniform than betatron beams at $100 \mu\text{s}$ but when integrating the intensity profile at greater times, RF-KO has an evident advantage. Figure 3 shows the comparison of Max/Mean at 10 kHz between betatron core and RF-KO extraction for protons beam at $2 \cdot 10^9$ protons/s and for carbon ions beam at $4 \cdot 10^7$ ions/s.

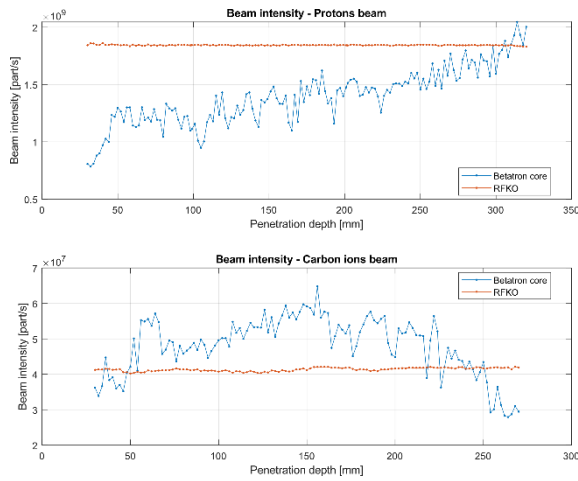


Figure 2: Measured beam intensities for protons and carbon ions with betatron core and RF-KO extraction.

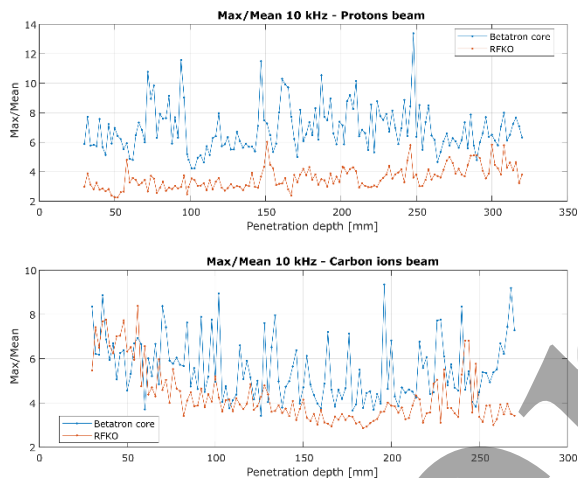


Figure 3: Comparison of proton and carbon ions beams spill intensity uniformity for betatron core and RF-KO extraction.

PROTON FOR OCULAR TREATMENTS COMMISSIONING

A specific tumour that CNAO treats is the ocular melanoma [6] by proton beams. Since the minimum extracted energy has a penetration depth of 30 mm, ocular treatments request the interposition of a range shifter before the dose delivery that shifts Bragg peak of 27 mm allowing to have protons with a 3 mm penetration depth.

Since ocular treatment are performed by the insertion of a clip in the patient eye and the irradiation must be synchronized with ocular movements, it is necessary that beam delivery lasts as little as possible: as a consequence particular attention must be devoted to extraction efficiency and beam intensity.

The electronics of the dose delivery chambers has a saturation limit of 20 counts/ μ s that gives strong constraints to the maximum number of counts and therefore to beam intensity and the Max/Mean of the spill time structure. Due to the speed of the air-core current power supply, when looking below the 100 μ s scale the max/mean ratio worsen so a limit on the maximum counts of 600 counts/100 μ s has

been considered as the commissioning target. This number is particularly critical also considering that the interposition of the ocular range shifter increases the collection efficiency of the chambers. For these reasons a specific commissioning has been performed for beam protons in the range 62.7–89.8 MeV dedicated to ocular treatments. After an optimization of synchrotron tune, RF-KO frequency and air core current feedback parameters, the maximum intensity obtained was a compromise between the highest feasible intensity thanks to the RF-KO 500 W amplifier and DDS saturation threshold. In particular two intensities have been obtained, one for the penetration depths between 30 mm and 45 mm and one for the range 46–60 mm.

In Fig. 4 proton intensities for ocular treatments are shown for the new RF-KO extraction and the betatron core extraction. Figure 5 compares Max/Mean values of the two extractions at a 10 kHz scale.

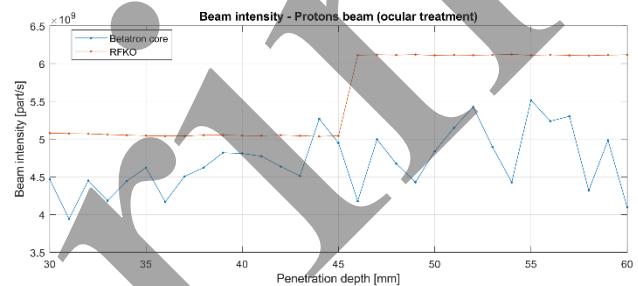


Figure 4: Intensity of protons for ocular treatments extracted with betatron core and RF-KO.

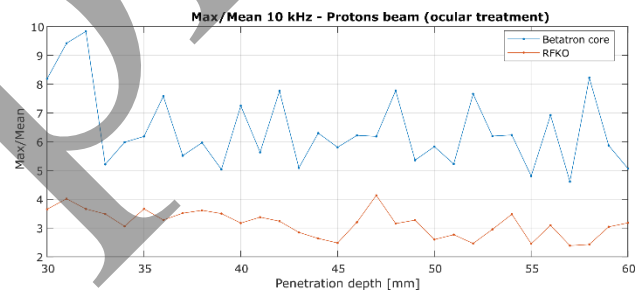


Figure 5: Spill uniformity comparison between betatron core extraction and RF-KO extraction protons for ocular treatments.

CONCLUSION

RF-KO extraction has been successfully commissioned at CNAO and beams have been clinically qualified making RF-KO the leading extraction method for the treatments with both proton and carbon ions beams, even for melanoma ocular treatments. This allowed a very precise control of intensity of extracted beams and will make possible the implementation of multi-acceleration cycles at CNAO in the next future.

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] S. Marangoni *et al.*, "Commissioning of Helium Beams at CNAO", presented at IPAC'26, Deauville, France, May 2026 paper THP4100, this conference
- [3] L. Falbo, E. Bressi, S. Foglio, C. Priano, "Betatron Core Slow Extraction at CNAO", CNAO Foundation, Pavia, Italy. doi:10.18429/JACoW-IPAC2018-TUZGBF3
- [4] 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
- [5] P. Meliga *et al.*, "Design and commissioning of the RF-KO extraction at CNAO", in *Proc. IPAC'23*, Venice, Italy, 2023, pp. 162-164. doi:10.18429/JACoW-IPAC2023-M0PA060
- [6] M. Ciocca *et al.*, "Design and commissioning of the non-dedicated scanning proton beamline for ocular treatment at the synchrotron-based CNAO facility", *Med Phys.*, 2019, vol. 46, no. 4, pp. 1852-1862. doi:10.1002/mp.133890

Preprint