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IMPLEMENTATION OF RF-KO EXTRACTION AT CNAO

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Abstract

The National Centre for Oncological Hadrontherapy (CNAO) is a synchrotron based particle therapy facility. Both protons and carbon ions can be used for treatments. The main extraction system is based on 'amplitude-momentum selection' driven by a betatron core, but RF-KO (Radio-Frequency Knock Out) is being implemented as an alternative extraction scheme, being more suitable for a future implementation of a 'multi energy extraction' operation of the accelerator. With a double extraction possibility, CNAO would allow an interesting theoretical and experimental evaluation of the relative merits of the two extraction schemes. The RF deflector is already installed and the RF power generation is under commissioning. Extraction simulations and first results of the system are presented.

INTRODUCTION

The CNAO (National Centre for Oncological Hadrontherapy) in Pavia is one of the six centres worldwide in which hadrontherapy is administered with both protons and carbon ions. The main accelerator is a 25 m diameter synchrotron designed for particle therapy which can accelerate energies up to 400 MeV/u for carbon ions and up to 250 MeV for protons [1]. To date 2300 patients have been treated, nearly 1400 with carbon ions (~60%).

For clinical treatments, a beam extracted in a slow controlled process over several seconds is necessary to facilitate measurement and control of the delivered radiation doses. Many techniques are possible to perform a slow extraction, as explained for example in the PIMMS [2].

The betatron core-driven 3rd order resonance extraction method has been chosen as the main method at CNAO and it is used to extract particles from the synchrotron in a spill time period between 1 and 10 seconds. The use of a betatron core offers an intrinsic robustness in minimizing intensity ripples and with the use of additional smoothing techniques the time structure of the spill is appropriate to treatments [3]. RF-KO is now being implemented as an alternative extraction scheme, being more suitable for multi energy extraction.

BEAM EXTRACTION AT CNAO

Slow extraction is performed with resonant schemes in which the machine is operated near to a third-order resonance (Q_x~N/3). Before extraction, a sextupolar field excites the 3rd order resonance, distorting the particle trajectories in the phase space and creating a triangular stable region outside which the motion of the particles becomes unstable. When the beam has to be extracted, the particles are brought out of the stable region, such that their betatron oscillation amplitude grows until they reach the extraction septum and are finally sent to the treatment room. The CNAO synchrotron tune at extraction is set near the third integer resonance (~5/3) and the horizontal chromaticity is quite large (~-4.0) [4]. The synchrotron optics is characterized by two superperiods for the betatron functions and two closed dispersion bumps. Dispersion is about 8 m in two opposite sides of the machine. Beam is accelerated with an average momentum spread of about $-3\cdot10^{-3}$; it allows having a stable beam (thanks to the large chromaticity) even if the machine tune is near a resonance.

To extract the beam, a betatron core accelerates the particles towards the unstable region. The stacking beam must have large momentum spread and flattened momentum distribution. 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 large and constant enough, RF cavity is switched off and the beam becomes a coasting beam ready for the extraction. RF cavity is then switched on during extraction, performing the so called Empty Sweeping Bucket [3], 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. The Empty Sweeping Bucket allows reducing the spill ripple and contributes to beam extraction.

Once the prescribed dose, for a specific energy, has been completely delivered, if there is still beam in the synchrotron, it is deflected against a dump, and then a new beam injection is required to treat at the next energy.

CNAO wishes to implement the so called ‘multi-energy’ extraction, which allows multiple energies to be delivered in a single synchrotron spill. The ability to deliver several energy layers per spill will reduce the time spent to reaccelerate the beam during patient treatment.

The betatron core extraction needs the beam to be debunched after the acceleration. Elsewhere, the acceleration of the non-extracted beam to the new treatment energy requires to turn on again the RF cavity, and thus to bunch the beam. Unfortunately, the bunching process is not efficient and makes multi-energy extraction not possible with such an extraction method.

RF-KO IMPLEMENTATION AT CNAO

RF knockout extraction is more suitable for a future implementation of multi energy extraction operation of

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the accelerator, since it does not need the de-bunching of the beam. In RF knockout extraction, the beam is excited in the horizontal phase space by a RF-transverse field. The amplitude of betatron oscillations increases and, without changing the tune of the particles, they reach the unstable region. The momentum spread of the extracted beam is equal to the momentum spread of the circulating beam, unlike the case of extraction with the betatron core.

The frequency of the RF signal must match, for each particle, the horizontal betatron frequency:

$$f_{RFKO} = \left(n \pm q_{x_p}\right) f_{rev} \qquad (1)$$

where f_{RFKO} is the RF signal frequency, q_{xp} is the fractional part of the particle horizontal tune, f_{rev} is the revolution frequency and n ∈ N.

The particles momentum spread determines the tune spread, due to the horizontal chromaticity. With a tune spread, a sweep in RF frequency is needed in order to cover all the particle tunes.

Particle frequency and tune can be written as function of the synchronous particle:

$$f_{rev} = f_0\left(\eta\frac{dp}{p} + 1\right)$$
$$q_{xp} = q_{x0} + \xi_x\frac{dp}{p} \qquad (2)$$

where f_0 is the revolution frequency of the synchronous particle, η the slippage factor and ξ_x the horizontal chromaticity. The combination of these equations leads to define, at first order in dp/p, the betatron frequency as reported in Eq. (3):

$$f_{RFKO,p} \approx f_0\left[(n \pm q_0) + \frac{dp}{p}\left(\xi + \eta(n \pm q_0)\right)\right] \qquad (3)$$

From Eq. (3), it is then possible to obtain the range of the RF-signal.

Simulations

Simulations of RF-KO extraction have been performed using MAD-X [5] code, for different values of the average momentum spread (-0.05%, -0.1% and -0.15%). Due to limitation in calculation time 10^4 particles (uniformly distributed) have been tracked for 10^6 turns (during clinical operation the number of turns needed for extraction varies between 10^6 and $3{\cdot}10^6$, depending on particle and energy). The resonance sextupole is turned on in 6000 turns. From simulation results, the maximum kick angle needed to distribute the extracted particles over 1s is about 1µrad.

Furthermore, the time structure of the extracted beam has been used as the main estimator to compare different amplitude modulation (AM) configurations. As it can be seen from Figure 1, a parabolic ramp, starting from 0.3 µrad and reaching 0.9 µrad over 10^6 turns, allows having a constant spill structure.

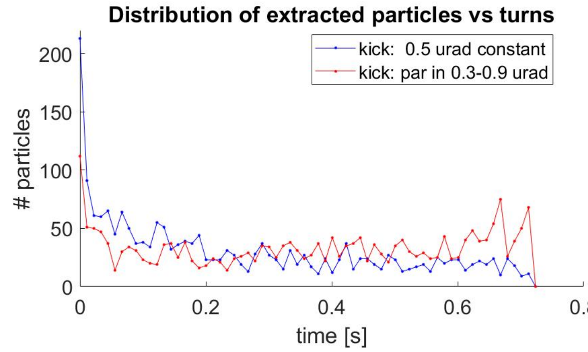

Figure 1: Spill time structure for different AM modulations, over 10^6 turns: the red line represents a constant kick of 1 µrad, the blue line represents a constant kick of 0.5 µrad, while the green one represents a parabolic trend from 0.3 µrad to 0.9 µrad.

Hardware

The RF-KO kicker has been installed in CNAO synchrotron in November 2018 (Figure 2).

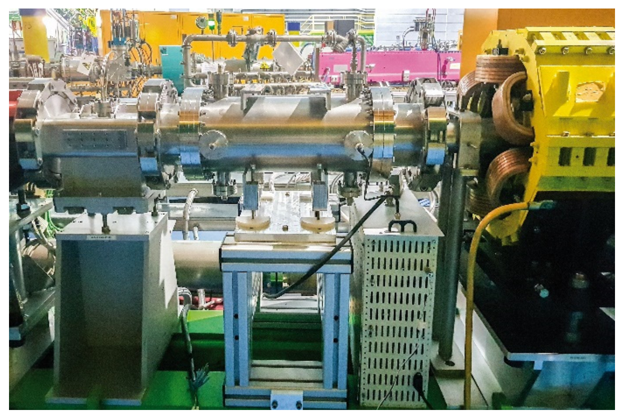

Figure 2: RF-KO kicker installed in CNAO synchrotron.

The deflection due to an electric field is computed as

$$\theta_x = tan^{-1}\left(\frac{|V_x| \cdot l_{eff}}{d \cdot p \cdot \beta}\right) \qquad (4)$$

with quantities defined as in Table 1:

Table 1: Physical Quantities Characterizing the CNAO RF-Kicker

Physical quantity	Unit	Meaning
θ	rad	Deflection angle
$\frac{\lvert V_x \rvert}{d}$	V/m	Electric field at kicker plates
l_{eff}	m	Effective length of the kicker
p	eV/c	Momentum of the beam
β	-	Relativistic Lorentz factor

The entire system is composed by a Low Level RF (LLRF), a 500 W amplifier, a RF-filter to drive the kicker plates in a differential way and a voltage divider to have a

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voltage feedback loop. The effective length of the CNAO RF-kicker is 37 cm, the electrodes gap is 137.24 mm and the simulated electric field between the plates is 2676 V/m (corresponding to 500 W). Consequently, the maximum deflection for the highest carbon ion energy (400 Mev/u) is 0.8 μrad.

COMMISSIONING STRATEGY

The commissioning strategy aims to find the best configuration that maximizes the extraction efficiency, characterizing the parameters of both the frequency modulation (FM) and the amplitude modulation (AM). To avoid hardware limitations during tests (500 W of the amplifier), it was decided to carry out the commissioning using the lowest proton energy (62 MeV).

The use of the RF-KO requires modifying the ring optics with respect to the one for extraction with betatron core. The involved parameters are: chromaticity, tune, average momentum spread, total momentum spread, position and divergence at the electrostatic septum and the strength of the electrostatic and magnetic extraction septa.

The chromaticity must be brought as close as possible to zero due to clinical requirements on dose homogeneity. Indeed, the synchrotron oscillations of the bunched beam have a frequency of about 1 kHz and would appear in the time profile of the extracted beam, because of the correlation between tune and momentum spread created by a large chromaticity.

The tune has to be chosen considering the losses due to the resonance sextupole. To find a new machine tune, a scan with the synchrotron quadrupoles has been performed changing the tune from the nominal value of 1.661 up to 1.760.

Figure 3 shows the extracted particles as a function of tune with $\xi_x = -0.1$ and when the RF-KO kicker is off. The extraction is fully caused by the resonance sextupole. The operating tune has to be chosen in such a way that no particles are extracted in this condition.

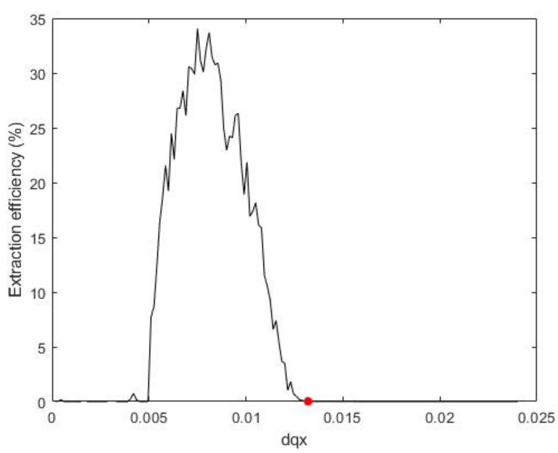

Figure 3: Extracted particles at different machine tunes due only to the effect of the resonance sextupole. Red point indicates the minimum tune that avoids an unwanted extraction.

Once the ring optics is fixed, the parameters of the RF-KO kicker will be defined.

Looking at Eq. (1), several quantities have to be optimized for RF-KO: tune harmonic (n), central frequency, shape of frequency modulation, frequency excursion and period of the frequency modulation. Two shapes for FM will be investigated: a saw tooth frequency profile and a random frequency profile.

After having fixed the frequency characteristics with a step of 1 μrad, different configurations of amplitude modulation will be tested, in order to keep constant the spill structure over the extraction time.

A feedback on the AM modulation is also probably necessary to reach the spill uniformity requested by clinical activities and, if needed, it will be implemented at the end of the tests previously illustrated.

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REFERENCES

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

[2] P. J. Bryant *et al.*, "Proton Ion Medical Machine Study (PIMMS) Part 1 and 2", *CERN/PS 1999-01-DI* (1999) and *CERN/PS 2000-007- DR*, Geneva (2000).

[3] E. Bressi *et al.*, "Empty Sweeping Bucket For Slow extraction", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, paper TUPAF010.

[4] E. Bressi *et al.*, "Betatron core slow extraction at CNAO", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, paper TUZGBF3.

[5] H.Grote, F. Schmidt, "The MAD-X program user's interface manual", Geneva, Switzerland, 2016.