RF-KNOCKOUT EXTRACTION SYSTEM FOR THE CNAO SYNCHROTRON

N. Carmignani, C. Biscari, M. Serio, INFN/LNF Frascati (Roma), Italy
G. Balbinot, J. Bosser, E. Bressi, M. Caldara, M. Pullia, CNAO Foundation, Milan, Italy
G. Venchi, University of Pavia, Pavia, Italy

Abstract

The National Centre for Oncological Hadrontherapy (CNAO) is a centre in Italy for the treatment of patients affected by tumours with proton and carbon ions beams accelerated in a synchrotron. The synchrotron extraction method is based on the use of a betatron core. This work aims to verify, through a theoretical study and a simulation, the possibility of using the RF-knockout extraction method exploiting the existing hardware. A simulation program has been written to simulate the extraction system of the synchrotron with the purpose to define the parameters of the radio frequency. Two types of radio frequencies have been compared in order to obtain a constant spill with the minimum ripple: a carrier wave with a frequency and amplitude modulation, and a gaussian narrow band noise modulated in amplitude. Results of the simulation and considerations on the kicker characteristics are presented.

INTRODUCTION

The Italian National Centre for Oncological Hadrontherapy (CNAO) will produce beams of protons accelerated up to $250\,\mathrm{MeV}$ and carbon ions up to $400\,\mathrm{MeV/u}$ [1]. The accelerator complex installation has been recently completed. The commissioning status description is presented in another paper in this conference [2].

The beam extracted from a hadrontherapy synchrotron must be uniform, low intensity and with a very stable spill, in order to facilitate the control of the radiation dose delivered to the patient.

The slow extraction of CNAO synchrotron is based on the third order resonance, excited by a sextupole magnet placed in a dispersion-free region.

The acceleration driven extraction with the use of a betatron core will be the primary extraction method. The possibility of using the RF knockout as an alternative method is here investigated.

The RF-knockout extraction method is used in other synchrotrons for hadrontherapy, for example HIMAC [3].

RF-KNOCKOUT

The RF-knockout extraction system involves the use of a kicker, which perturbs the beam horizontally (Figure 1). The frequency of the signal given to the kicker is of the order of the revolution frequency [4].

The frequency of the RF signal must match the horizontal betatron frequency:

$$f_0 = (n \pm q_x) \times f_{rev} \tag{1}$$

where f_0 is the RF signal frequency, q_x is the fractional part of the horizontal tune, f_{rev} is the revolution frequency and $n \in \mathbb{N}$.

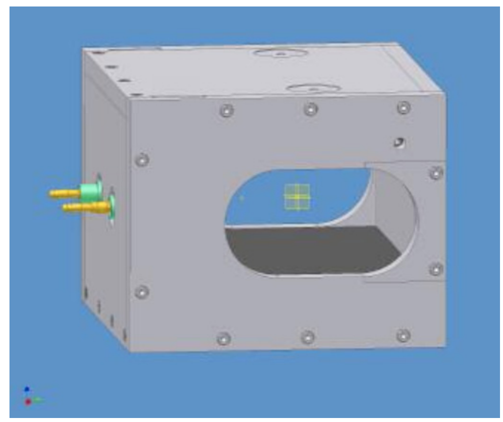

Figure 1: Tune kicker.

The particles momentum spread determines a tune spread, due to the horizontal chromaticity. It can be derived as:

$$\Delta Q_x = |\xi_x| \times Q_x \times \Delta p/p \tag{2}$$

where Q_x is the horizontal tune, ξ_x is the horizontal chromaticity, p is the reference momentum, Δp is the momentum spread.

With a tune spread, the RF frequency must vary to cover all the particle tunes.

Two possible signals are studied: a sinusoid with a sawtooth frequency modulation and a noise in the range of frequencies suitable to cover all the tunes.

To have a constant rate of extracted beam, the amplitude of the RF signal must be increased during the extraction [3].

SIMULATION

A dedicated simulation program has been written in C++ language to track the particles in the synchrotron with the RF-knockout.

The program performs a six-dimensional tracking. Any number of particles can be tracked for any number of turns in the synchrotron. The RF signal can be defined by the user. The synchrotron lattice and the initial particle coordinates are the input of the program.

The program generates a particle distribution uniform in an ellipse in the horizontal and vertical phase space. The momentum spread is $\Delta p/p = 0.001$.

The tracking of the particles through the linear segments of the synchrotron is performed calculating the corresponding first order transfer matrices. The tracking through the sextupoles and the kicker is performed with the thin lens approximation.

The beam parameters used for the simulation are relative to the carbon ions beam at maximum energy, which are the most demanding in terms of kicker strength, and they are shown in Table 1.

Table 1: Characteristics of the Simulated Beam

Particle	$^{12}C^{6+}$
kinetic energy	400 MeV/u
$\epsilon_x = \epsilon_y$	3.66225 mm mrad
Q_x / Q_y	1.672 / 1.722
$\xi_x Q_x$ / $\xi_y Q_y$	-3.940 / -1.067
$\Delta p/p$	0.001
ΔQ_x / ΔQ_y	0.004 / 0.001
f_{Rev}	2.757 MHz
$f_{Rev} \cdot \Delta Q_x$	11 kHz

RF-signals

An RF signal modulated in frequency has the following form:

$$k(t) = k_0 \times \cos(\omega_0 t + \phi(t)) \tag{3}$$

where k_0 is the maximum amplitude of the signal, ω_0 is the carrier wave pulsation and $\phi(t)$ is the frequency modulating signal.

The instantaneous frequency is:

$$f(t) = \frac{\omega_0}{2\pi} + \frac{1}{2\pi}\frac{\mathrm{d}\phi(t)}{\mathrm{d}t} = f_0 + G(t) \tag{4}$$

A signal that matches all the frequencies of the beam must change the instantaneous frequency. The easiest way is to use a sawtooth function as function $G(t)$.

The sawtooth function frequency chosen is 1 kHz, the peak to peak amplitude is 20 kHz.

A noise signal in the range of frequencies of the beam particles has been obtained with the C++ pseudo random number generator. That signal has been filtered with a gaussian filter. The noise spectrum is shown in Fig. 2.

FM

Frequency modulated signal covers all frequencies of the beam, but the extracted beam has a ripple corresponding to the frequency of the modulating function.

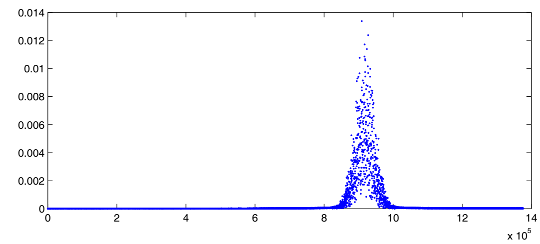

Figure 2: Fast Fourier Transform of the noise signal.

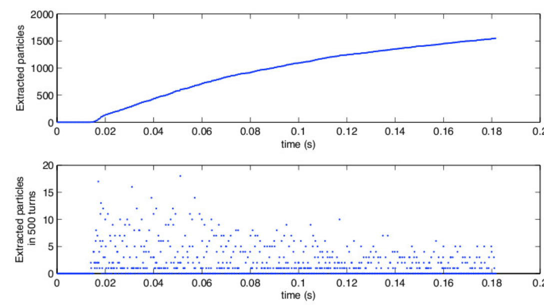

Figure 3: Extraction with constant kick amplitude.

The intensity of the extracted beam decays exponentially, as shown in Fig. 3.

In Figure 4, the integral of extraction current is shown together with the saw-tooth frequency modulation signal for a short time, so the 1 kHz ripple is visible.

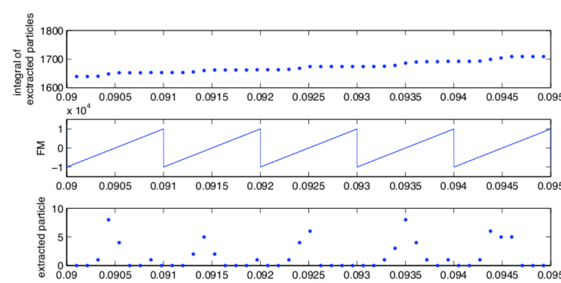

Figure 4: Integral of the spill; saw-tooth FM; spill.

Noise

Although the RF-knockout with the noise signal is not used in the main synchrotrons for hadrontherapy, the simulation shows that the ripple is eliminated from the spill with that method. Figure 5 shows the spill characteristics for this case.

AM

The spill decays exponentially with time. The characteristic time of the exponential depends on the kick amplitude.

In Figure 6, the inverse of the characteristic time ($\lambda = 1/\tau$) is plotted as a function of the kick amplitude.

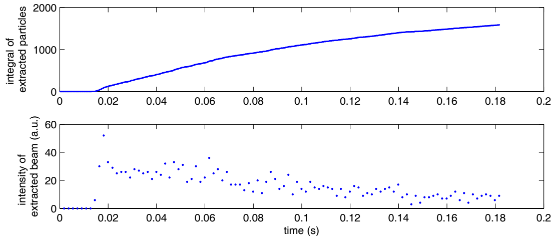

Figure 5: Integral of the extracted beam; spill.

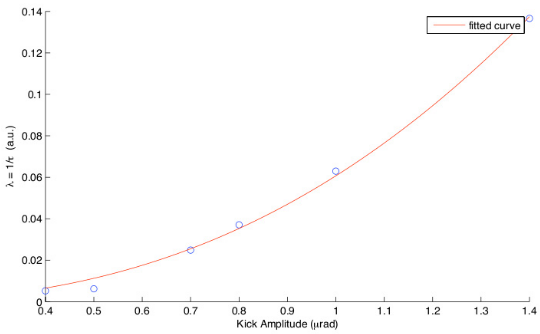

Figure 6: $1/\tau$ as function of kick amplitude.

A fit with a power function $\lambda = A \times k^B$ has been performed, in order to find the best approximation. It is an empirical way to to estimate the value of $1/\tau$ as function of the kick amplitude.

$$B = 2.4 \pm 0.1 \tag{5}$$

The extracted beam has an exponential decay:

$$\mathcal{N}(t) = \mathcal{N}_0 \, e^{-\frac{t}{\tau}} \tag{6}$$

where $\mathcal{N}(t)$ is the number of particles of the beam at time t, $\mathcal{N}_0$ is the initial number of particles.

$$-\frac{\mathrm{d}\mathcal{N}(t)}{\mathrm{d}t} = \frac{\mathcal{N}(t)}{\tau} = \mathcal{N}(t) \times \lambda \tag{7}$$

The amplitude of the kick must be increased to have a constant spill.

$$-\frac{\mathrm{d}\mathcal{N}(t)}{\mathrm{d}t} \propto \mathcal{N}(t) \times k(t)^B = const = \mathcal{N}_0 \times k_0^B \tag{8}$$

$$k(t) = k_0 \times (\mathcal{N}_0/\mathcal{N}(t))^{1/B} \tag{9}$$

where $\mathcal{N}(t) = \mathcal{N}_0 \times (1 - t/\tau)$.

In Figure 7, the kicker amplitude has been increased with the amplitude modulation function of equation 9.

Spill integrals of 0.1 s long periods in different moments have been compared and they differ by about 10% for the first 70% of the extraction.

A feedback system could be useful to have a constant extraction of the last part of the beam.

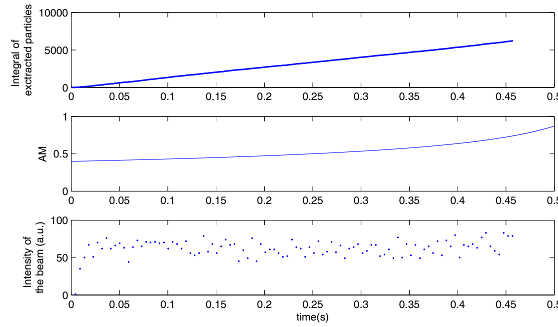

Figure 7: Spill integral, AM, spill.

Hardware

The maximum amplitude of the kick, as shown by simulation, is about $1\,\mu$rad. Two devices could be used for the RF-knockout extraction in CNAO synchrotron: the tune kicker and the Schottky pickup [5] [6].

The tune kicker is a dipole used to measure the horizontal tune. The beam can be deviated by its magnetic field. The Schottky pickup is a diagnostic element of the synchrotron with stripline electrodes. It can be relatively easily turned in a beam kicker.

CONCLUSIONS

After analysis and evaluations, the feasibility of the RF-knockout extraction in the CNAO synchrotron has been checked.

Two signals have been compared for the RF-knockout extraction. With the frequency modulated signal, the extracted beam has a ripple at the frequency of the modulating signal (1 kHz). The noise signal does not produce an extracted beam with ripple, so it is preferable.

A flat spill is possible with an amplitude modulation of the signal. The simulation showed that for the first part of extraction the intensity is constant within a fluctuation less than 10%. To get a constant extraction also for the last part, a feedback system could be useful.

REFERENCES

[1] M. Pullia, Proceedings of EPAC08, TUOCG02, 2008.

[2] G. Bazzano, this conference, MOPEB005.

[3] T. Furukawa et al., Nuclear Instruments and Methods in Physics Research A 522, 2004.

[4] S. Van der Meer, CERN/PS/AA 78-6, 1978.

[5] J. Borburgh et al., CNAO Technical Note CNA-TNDP-006WXX-00231, 2003.

[6] M. Caldara, A. Parravicini, CNAO Technical Note CNA-TNDF-011WXX-03821, 2004.