Slow extraction modelling for NIMMS hadron therapy synchrotrons

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Abstract. The Next Ion Medical Machine Study (NIMMS) is an umbrella R&D programme for CERN accelerator technologies targeting advanced accelerator options for proton and light ion therapy. In collaboration with the European programme HITRIplus, one area of study is slow extraction which is required to deliver a uniform beam spill for radiotherapy treatment. Several techniques use the third-order resonance to extract hadrons; these include betatron core driven extraction and radiofrequency knock-out. Flexible simulation tools using these techniques were prepared and initially benchmarked with results from the literature that used the Proton-Ion Medical Machine Study (PIMMS) design. The limits of the current PIMMS design were then pushed to evaluate its compatibility to deliver 10x higher intensity ion beams, and using increased extraction rates.

1. Motivations

Flexible modelling techniques have been developed to facilitate the design of NIMMS [1]. The NIMMS study has a variety of designs available including normal and superconducting options [2]; all aiming to provide a variety of light ion beams for clinical treatment and radiobiological research.

Resonant slow extraction is used to ensure a continuous and stable dose delivery during treatment. It is performed by setting the horizontal tune of the machine close to the third-order resonance (Q_x =1.666) which is excited with strong resonant sextupole magnets. The particles are then driven to the resonance via excitation methods, leave the stable triangle phase-space and are extracted at the electrostatic septum (ES).

Simulations of slow extraction were used to assess if the PIMMS [3, 4] design, as utilized by CNAO and MedAustron therapy facilities, can be adapted to suit advanced accelerator options. The feasibility study was performed, first by modelling the PIMMS lattice, then changing excitation methods to ensure it can be upgraded to meet two requirements: adapting to extract higher emittance beams, and providing the option of increased extraction rates.

1.1. Higher emittance

Multi-Energy Extraction (MEE) uses multiple flat-tops for each required treatment energy, rather than having one energy per magnet duty cycle. This technique decreases wait-time during delivery of different energies, and was proposed and implemented at the NIRS HIMAC center [5].

To deliver a dose of 2 Gy to a 1-liter tumour within one cycle of MEE, the synchrotron must store 1 to 2×10^{10} carbon ions [2], which is 20× higher than what current European hadron therapy synchrotrons can deliver. With an ion source of 600 µA, a multi-turn injection method of 30 turns needs to be performed to achieve this higher intensity, assuming 50% injection efficiency. This method would consequently generate a horizontal, normalised rms emittance increase of $\varepsilon_{x_{\rm rms}} < 6\pi$ mm mrad. Slow-extraction studies have been performed to assess the fesibility of extracting a beam with these larger emittances.

1.2. Increased extraction rates

Treating with dose delivery rates of 50-100 Gy s^{-1} reduces toxicities to healthy tissue compared to conventional radiotherapy [6]. This technique is known as FLASH therapy. With a suggested threshold dose of 10 Gy, the beam should be provided within 100 ms [7]. The NIMMS synchrotron should provide a hadron beam which can meet the recommended dose within this time frame. The PIMMS revolution frequency for high-energy carbon is 2.8 MHz [4] so 100 ms requires 280,000 turns. This is a challenge compared to nominal slow extraction which delivers over millions of turns. This study will observe whether a high quality beam spill can be provided within this increased extraction rate.

2. Method

Simulations were performed to reproduce slow extraction results from the existing PIMMS synchrotrons, then these were adapted to meet the two advanced options. The lattice was implemented into MAD-X [8] and matched for the extraction conditions for two excitation methods: betatron core and radiofrequency knock-out (RKFO).

The main lattice parameters relevant to slow extraction are horizontal and vertical tune Q_x, Q_y, chromaticity Q'_x, virtual sextupole strength $S_{\rm virt}$ and beam momentum spread $\frac{\Delta p}{p}$, shown in table 1 for both methods.

Table 1. Lattice extraction parameters.

	Q_x	Q'_x	Q_y	$S_{\rm virt}$	$\Delta p/p$
Betatron	1.666	-4.041	1.720	28.4	0.4%
RFKO $1\varepsilon_x$	1.675	-0.004	1.695	32.1	0.1%
RFKO $6\varepsilon_x$	1.680	-0.007	1.695	32.1	0.1%

The resulting lattice is converted into a high order Polymorphic Tracking Code (PTC) map [9] using the Maptrack module [10, 11], written in python. Maptrack's ability to split a 1-turn map into segments was employed, and custom elements were written in-between map segments, creating dynamic simulations of betatron core and RFKO excitation. The tracked beam was a 400 MeV/u energy carbon beam with a gaussian beam profile corresponding to normalised rms emittance of $\varepsilon_{x_{rms}} = 1\pi$ mm mrad. Each turn, the beam was observed at the position of the electrostatic septum.

Visualisation tools were developed to observe the phase-space evolution and tune change of the beam throughout slow extraction. An interactive demonstration of these tools is in development [12]. The tune is calculated by measuring the fundamental frequency of the particle's position in the x or y plane, over a window of 256 turns, using the Python NAFF module [13].

2.1. Betatron core
PIMMS synchrotrons use betatron core excitation, which decreases the momentum of the particles each turn to push their tune towards the resonance [3]. The dynamics was modelled by changing the particle momentum by a step corresponding to the tune distance to resonance, divided by chromaticity and total number of turns: $(Q_{x\text{res}} - Q_{x\text{min}})/(Q'_x \cdot N_T)$.

In operation, this method requires a debunched beam, therefore is difficult to combine with MEE, and so the excitation method of the NIMMS synchrotron must be adapted accordingly.

2.2. RFKO
RFKO excitation consists of two electrostatic plates which provide a transverse kick at frequencies close to the betatron tune, to increase the amplitude of the particles. It is the method in use at HIMAC [14] and HIT [15] and is currently being implemented at CNAO [16] and considered for MedAustron [17]. The method allows for extraction to start and stop rapidly, so it is ideal for MEE. Equation (1) [18] shows how the voltage V_p relates to the angular kick to a beam of charge-mass ratio Z/A and relativistic particle velocity $\beta = v/c$. The kick strength depends on the properties of the exciter: length L and plate distance a.

$$\theta_k = \frac{Z}{A}\frac{e}{m_p}\frac{V_p}{a}\frac{L}{\beta^2 c^2} \tag{1}$$

The RFKO exciter installed at CNAO is located in-between the injection septum and the first chromatic sextupole. It has a maximum voltage of 367 V, corresponding to a kick of 2.8 µrad for 250 MeV protons and 1.0 µrad for 400 MeV/u carbon ions [16].

Equation (2) is used to incorporate this effect into simulations, with the kick in particle angle, $\delta x'$ relating to amplitude θ_k, fractional tune of the beam q_x and turn number T.

$$\delta x' = \theta_k \cos(2\pi q_x T) \tag{2}$$

A gaussian range of frequencies around q_x is considered, to excite the tune spread of particles. An amplitude curve is added throughout extraction which exponentially increases with time to overcome the increased density of the particles at the core, the function of which is in use in operation at HIT [18].

2.3. High emittance simulations
Conventional betatron core can accommodate larger amplitudes, however RFKO is amplitude-driven, therefore an increase in amplitude requires a shift in slow extraction settings to avoid the initial beam being affected by the extraction region.

Two emittance increases were considered, $\varepsilon_x = 3$ and 6π mm mrad. Extracting a 3π mm mrad beam is compatible with nominal slow extraction settings, however a 6π mm mrad beam is too large for the stable phase-space region, and therefore the distance to the tune had to be increased to accommodate for this, see table 1. Alternatively, it is possible to keep the Q_x constant and decrease S_{virt}, however this would affect the spiral step - defined as final step of the particles before extraction.

3. Simulations
Using nominal betatron core extraction with a momentum shift of -3.2×10^{-9} per turn, the particles are considered extracted when they exceed the electrostatic septa aperture limit of x_{ES} =35 mm. The intensity drop of the beam and the spill showing number of particles extracted as a function of number of turns is represented in figure 1, which shows 5,000 particles extracted throughout 2,800,000 turns - equivalent to 1 s of spill.

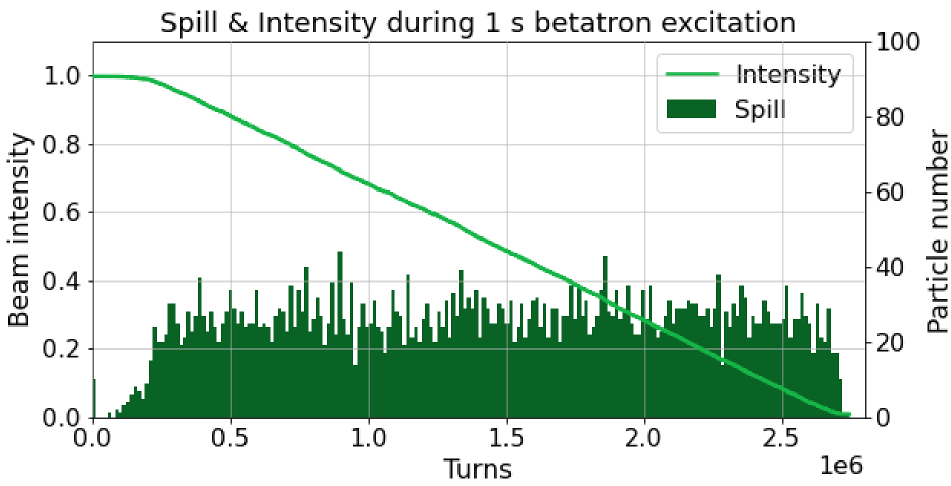

Figure 1. Beam and spill intensity as a function of turn number. 5,000 particles during 1 s of betatron excitation.

Figure 2 (top) in green shows the phase space and the Steinbach diagram [3] – tune vs amplitude – for a sample of 500 particles, cumulated over 25 turns, during which a particle is extracted. The large x_p distribution is due to the momentum increase and the cumulative visualization in a point with non-zero dispersion.

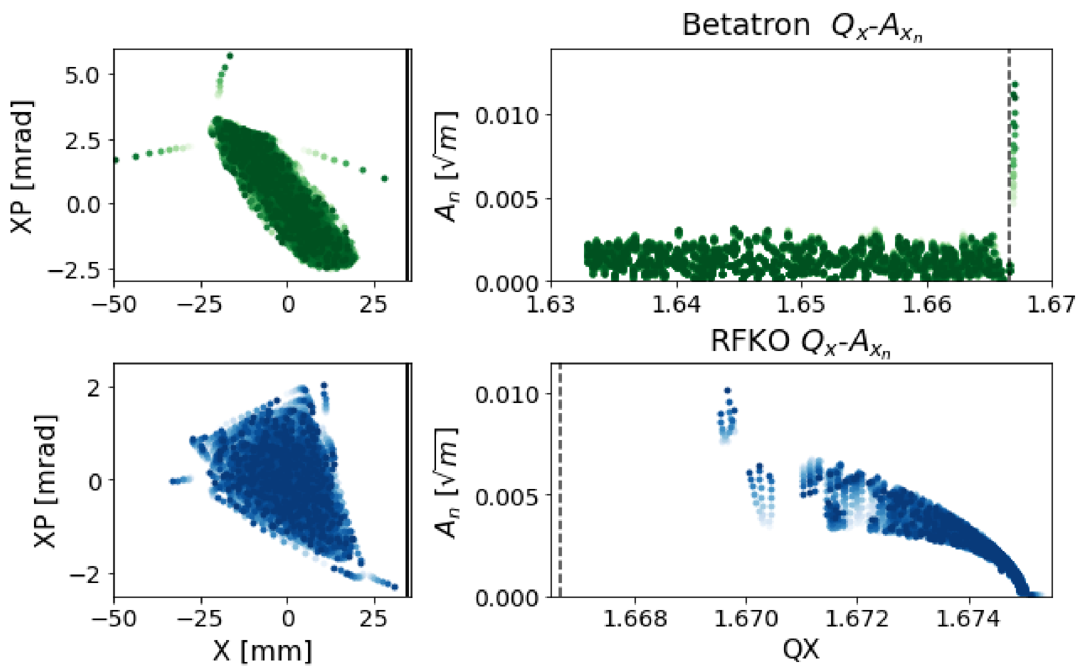

Figure 2. Cumulative phase-space and Steinbach diagram of 500 particles, 25 turns, for betatron (top - in green) and RFKO (bottom - in blue) extraction.

In figure 2 (bottom) in blue, the phase-space and tune evolution during RFKO excitation is shown. The left plot shows that the stable triangle phase-space is larger, and the right plot shows that when the particle's amplitude increases due to the $\delta x'$ kick, it experiences detuning, causing them to approach the resonance before extraction.

This RFKO excitation was then performed for 5,000 particles over 2,800,000 turns, and figure 3, in blue, shows the number of particles extracted per turn and the resulting beam intensity decrease, for an emittance of 1π mm mrad. The amplitude of the RFKO kick strength for this extraction spill is plotted as the dashed blue line in µrad, and varies between 1-2 µrad, which is compatible with previous RFKO simulations of PIMMS machines [19].

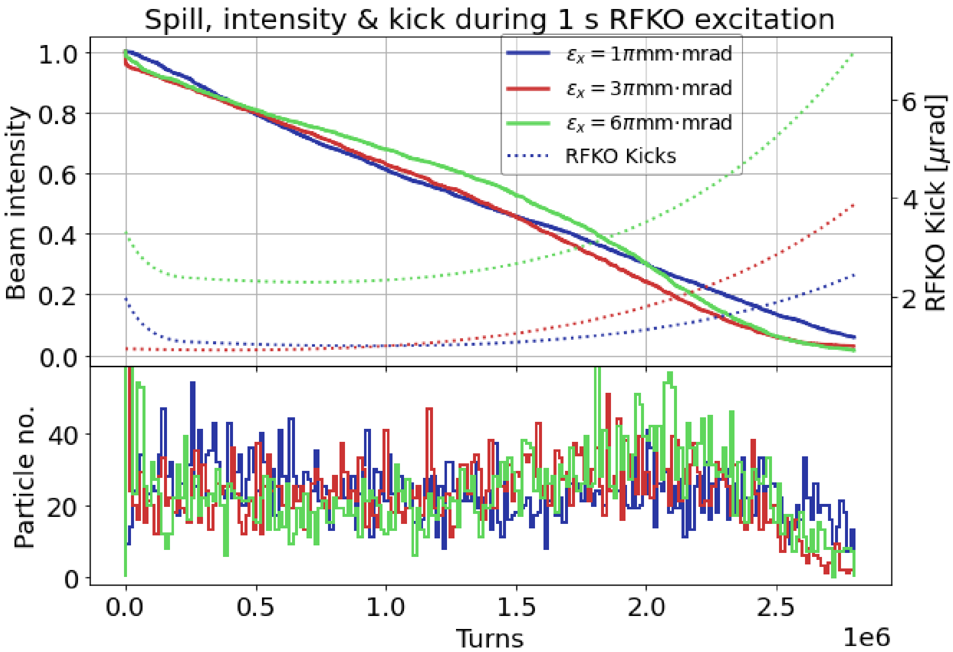

Figure 3. 5,000 particles extracted via RFKO over 1 s for three initial emittances, with optics settings as per table 1.

The effect of increasing the emittance to 3π mm mrad, is shown in figure 3 in red, and shows it is compatible with the nominal RFKO optics, but requires increases to the RFKO kick function for higher turns. Increasing emittance to 6π mm mrad requires moving the tune away from the resonance, as shown in table 1, else a substantial amount of the beam is extracted within the first few turns. The larger tune distance results in a larger required kick amplitude, between 1.5 to 3×, to extract the particles at the same rate.

To verify the validity of RFKO as a method for FLASH extraction, first the conditions required for a suitable spill timescale must be established, and then the feasibility of these conditions should be evaluated. Figure 4 shows that for a uniform spill totalling 10,000 particles over 280,000 turns (100 ms), the necessary RFKO kick varies between 2 µrad - 12 µrad, which is up to 6× higher than the kick used for 1 s of spill at the same emittance. From equation (1) for a CNAO-based exciter, this is equivalent to a voltage range from 700 V - 4.2 kV.

4. Conclusion

With MAD-X and Maptrack [10, 11] as a basis, flexible tracking and visualisation tools were developed for the slow extraction modelling of the PIMMS machine, with the intention of upgrading it to suit NIMMS advanced accelerator options. First the spill and behaviour of extraction was characterised for nominal betatron core excitation, and then the optics were

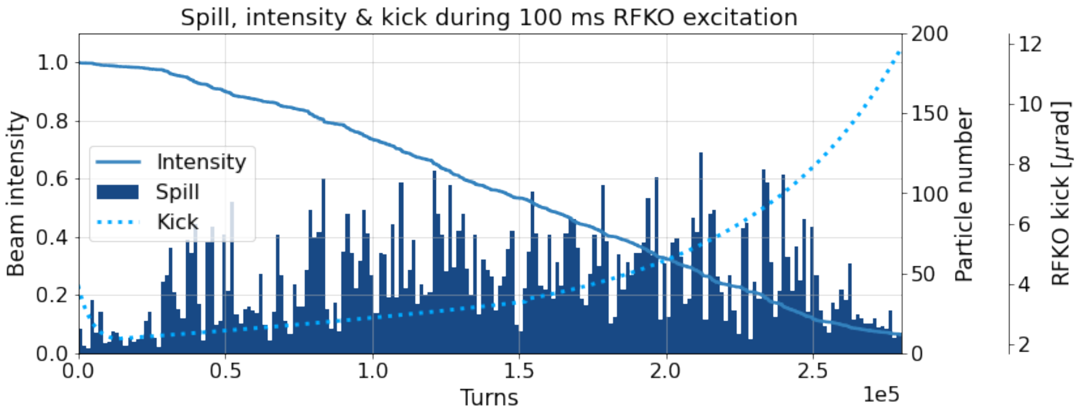

Figure 4. 10,000 particles extracted via RFKO over 100 ms.

adapted for RFKO excitation. Uniform spill could be produced by increasing the RFKO kick exponentially with time [18], and extracting higher emittance is possible by shifting the tune of the beam away from the resonance and providing a higher amplitude kick. Delivering a beam within 100 ms can be achieved by providing RFKO kicks on the order of 10 μrad, although the voltage required to provide kicks of this strength is on the order of kilovolts, which is difficult to achieve with existing hardware.

To gain experimental validation for both high emittance and high rate extraction, tests will need to be performed on an ion synchrotron to measure the voltage limits of existing RFKO exciters. It should be possible to observe how much of the beam can become extracted when the exciter is turned to its maximum strength. If this is not possible, alternative extraction techniques will need to be determined to meet FLASH conditions. The alternative FLASH techniques that are also compatible with bunched beam are based on optics changes. For example, tune sweep through the resonance can be done quickly using air-core quadrupoles or Constant Optics Slow Extraction (COSE) [11], which can potentially generate very fast extraction. Application of these two techniques alone or in a hybrid scheme with RFKO shall be investigated to determine the beam extraction scheme optimal for FLASH therapy.

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