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Simulation study on control of spill structure of slow extracted beam from a medical synchrotron with feed-forward and feedback using a fast quadruple magnet and RF-knockout system

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ABSTRACT

A feedback control of the spill structure for the slow beam extraction from the medical synchrotron using a fast quadruple and radio frequency (RF)-knockout (QAR method) is studied to obtain the designed spill structure. In addition the feed-forward control is used so that the feedback control is performed effectively. In this extraction method, the spill of several ms are extracted continuously with an interval time of less than 1 ms. Beam simulation showed that a flat spill structure was effectively obtained with feed-forward and feedback control system as well as a step-wise structure which is useful for the shortening of an irradiation time in a spot scanning operation. The effect of current ripples from main quadruple magnet's power supplies could be also reduced with the feedback control application.

1. Introduction

A synchrotron has been used for a cancer therapy with proton or carbon beams. A spot scanning irradiation requires a fast beam-on/off control in a slow beam extraction from a synchrotron to give the best flux distribution [1]. A radio frequency (RF) knockout method (RF-knockout method) based on the transverse beam heating at a constant separatrix is used in several facilities for the slow beam extraction [2], for example at the Heavy Ion Medical Accelerator in Chiba (HIMAC) [3,4]. The beam-on or -off times are reported as the order of 1 ms [2]. The present authors have developed a new extraction method which has a shorter beam-on/off time and a smaller variation of spill intensity. This method uses the control of a quadruple field of fast response as well as the RF-knockout [5]. The operational sequence of this method is as follows: (1) The separatrix area for the horizontal betatron motion under a resonant condition is slightly shrunk with the excitation of a fast Q-magnet (FQ), and the particles protruded from the separatrix are extracted, (2) the FQ is turned off after a required number of particles are extracted, (3) the circulating particles are diffused by the RF-knockout just inside the separatrix, and (4) the above process is repeated at every spot scanning cycle until the entire circulating particles are extracted. In this method (QAR[1] method), the spills of extracted beam of several ms width are realized with an interval time less than 1 ms. Thus the QAR method could control the beam extraction process with a fast response time since the extraction could be performed only with the adjustment of a quadruple field.

A desired dose to a spot is delivered during one excitation of the FQ, and the next spot is irradiated with the subsequent excitation of the FQ. A spill intensity during an extraction is required to be uniform to obtain the accurate dose, because a flux monitor for measuring a net dose has a response time and moreover there is a delay in switching off the beam [6]. To obtain a uniform spill structure, a circulating beam must be diffused uniformly by the RF-knockout. It is attained by an RF signal of multi-band spectra including many bands around the betatron resonances [7,8], but in a reality the uniform diffusion is difficult to be realized at every cycle. Moreover, a circulating beam has mostly the Gaussian distribution, not the uniform density distribution in the phase spaces, and therefore a feedback (FB) control of the current of power supply of the FQ is required for obtaining the designed spill structure.

The present paper describes the results of a case study with beam simulation of the FB control for the QAR method. A feed-forward (FF) control of the FQ, which optimizes a waveform of FQ's coil current, is combined to perform the FB control effectively. An effect of current ripples from the main magnet's power supplies is also simulated with the FF and FB control.

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[1] The QAR is an abbreviation for the slow extraction method using a fast Quadruple magnet Assisted by RF-knockout

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Table 1
Basic beam parameters for simulation.

Kind of ions	Carbon
Kinetic energy [MeV/u]	400
Circumference [m]	61.5
Average radius [m]	9.8
Betatron tunes (ν_x/ ν_y)	1.68/1.13
Max. betatron amplitude (β_x/β_y) [m]	~11/~13
Max. horizontal dispersion value (η_x) [m]	~5
Transverse emittance (ε_x/ε_y) [πmm·mrad]	3.5/0.5
Momentum spread	$\pm 3\times10^{-4}$
Revolution frequency [MHz]	3.483

2. Outline of beam simulation

Beam simulation of feed-forward and feedback controls for the QAR method was performed using a lattice structure similar to a compact synchrotron [9] designed at National Institute of Radiological Sciences (NIRS) where the HIMAC is running for the treatment of patients. The basic beam parameters for the simulation are given in Table 1. A layout of the compact synchrotron designed at NIRS is shown in Fig. 1. The bare betatron tunes at the beam extraction were ν_x=1.68 and ν_y=1.13, respectively. An RF signal for the RF-knockout was composed of multi-band spectra which contained frequency bands around the resonances of n+1/3 and n+2/3 (n=0, 1, 2, 3, 4).

The separatrix was produced by two sets of sextuple magnets (SXFr and SXDr) whose magnetic fields were increased linearly and adiabatically to the designed value within the time period corresponding to 30,000 turns. After that, particles located in the central area of the separatrix was diffused with the RF-knockout to increase a particle density near the separatrix. The operation time of the RF-knockout was 10,000 turns.

Following this RF-knockout application the FQ and the RF-knockout were operated alternately to extract the beam. An application period of the FQ was 6800 turns for rising and 100 turns for falling, and that of the RF-knockout was 3000 turns. The one cycle of operation of FQ+RF-knockout was 10,000 turns including a standby time of 100 turns, where a revolution period was 0.29 μs. The RF-knockout parameters of the kick angle and the frequency bands were determined so that the number of particles extracted during one operation of the FQ was 1% of the initial number of particles with a shrink rate of the stable area of 20%. Here the shrink rate is defined as dA/A with the stable area of A. A length of the FQ was set to be 7.14 cm, and the shrink rate of 20% was attained at a K-value of 0.00428 m^{-2}. Each frequency band of the multi-band spectra was set to n+0.32–n+0.325 and n+0.675–n+0.68 normalized by a revolution frequency of the synchrotron, 3.483 MHz. The frequency bands were set as being slightly apart from the exact third order resonances. This is because the diffusing of particles in the center region should be effectively larger than the diffusing near the separatrix [10].

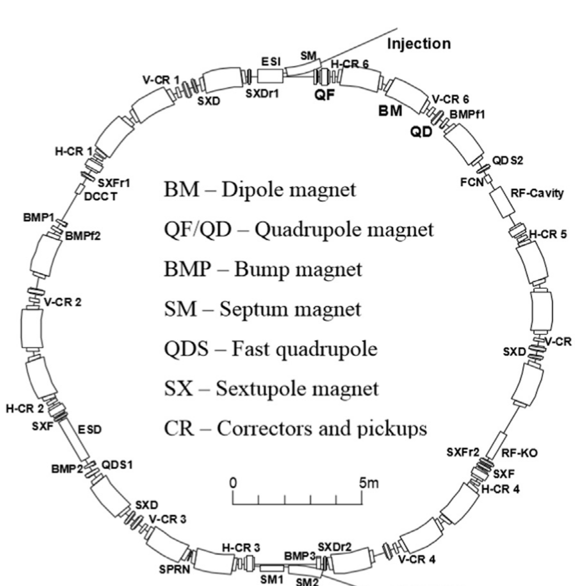

Fig. 1. Layout of a compact synchrotron [9] used for beam simulation.

The separatrix area is changed with the variation of FQ current which results in the change of divergence of extracted particles. A maximum position deviation of the particle due to this deviation of extracted angle was about 1 mm at an irradiation point of a high energy beam transport line (HEBT) of HIMAC. However, this level of deviation could be corrected easily with a fast controlled steering magnet installed at HEBT if necessary.

A septum of the synchrotron was set to 5.5 cm outside of an equilibrium orbit, and its gap and thickness were 1 cm and 0.03 cm, respectively. Simulated particles were assigned to be extracted when they entered into the gap. The extraction efficiency was typically counted at 94%. An initial distribution of particles was assumed as Gaussian and the horizontal and vertical emittances were 3.5 and 0.5 [πmm?mrad] with $\sigma\times\sigma'$, rms value, respectively. The initial distribution was calculated as follows: (1) Two sets of uniform random numbers between 0 and 1 were produced, (2) two sets of independent stochastic variables of the Gaussian distribution were obtained from the random numbers using Box-Muller's method, and (3) they were transformed to elliptical shape using the twiss parameters to be matched with the real particle distribution in the ring. The simulation was performed with a longitudinal RF-off condition, namely for the debunched beam, and the momentum spread was neglected to simplify the simulations. The change of betatron tune due to the momentum spread was also neglected since the chromaticity can be corrected.

3. Feed-forward control

The deviation of spill intensity from a designed value is very large at the beginning of beam extraction for the FB control, since a transverse density distribution of a circulating beam is assumed to be Gaussian distribution where the particle density is decreased to zero toward the separatrix and it is very low just inside the separatrix. Fig. 2 shows a spill structure when the FQ field is increased linearly. It is found that

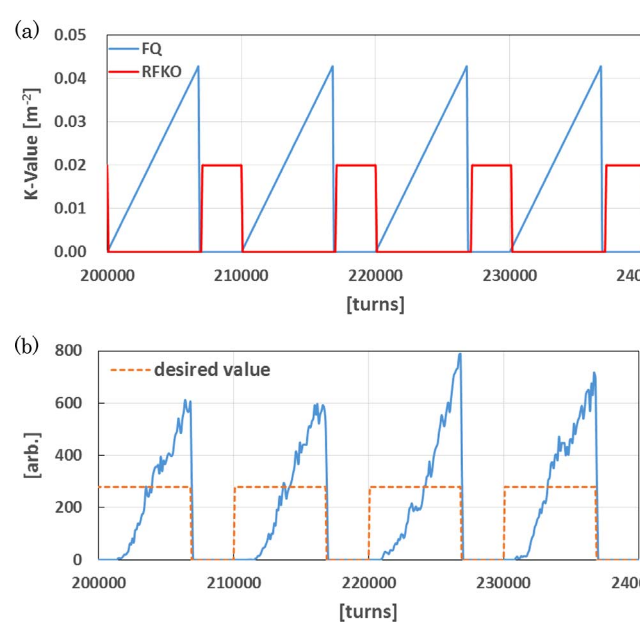

Fig. 2. Time chart of the FQ and the RF-knockout (a), and spill structures with the operation of the FQ and the RF-knockout (b).