DIFFUSION OF A CIRCULATING BEAM BY THE RF-KNOCKOUT WITH A SPECTRUM INCLUDING MANY BANDS

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Abstract

Diffusion of a circulating beam by the RF-knockout was studied on colored noise signal of the RF-knockout. It is found that frequency bands solely around the resonances (n+1/3 and n+2/3) contribute to the diffusion and the uniform spill, or equivalently uniform diffusion requires to include many bands around the resonances. A multi-bands spectrum including only such bands prevents an increase in power of an amplifier. It is also useful to increase a spill intensity in the QAR method by adjusting a bandwidth of all bands. The multi-bands spectrum was produced with preliminary experiment.

INTRODUCTION

In the case of spot scanning irradiation for the cancer therapy application, a fast control of beam extraction from a synchrotron is a key function [1]. An author proposed a beam extraction method which uses the control of a quadruple field of fast response as well as the RF-knockout (RFKO) (QAR method) [2]. The quadruple field is used for the extraction by shrinking a separatrix, and the RFKO for diffusion of a circulating beam. After the diffusion, the particle density in the separatrix is desirable to be as smooth as possible for obtaining a flat spill structure of the next extracted beam. It was shown in both beam experiment and simulation that the density distribution becomes no smooth even if the RFKO signal with a colored noise covers a frequency band corresponding to a tune spread, and a wider band spectrum is required for the smooth distribution. [3]

So far we proposed a multi-bands spectrum as the RFKO signal, which has a wider band without increasing the signal power [3]. A uniform diffusion was obtained by a beam simulation with a continuous RFKO operation (no use of the FQ) using such a spectrum. In this paper, a preliminary experiment for the multi-bands spectrum is described as well as optimization of the spectrum for the QAR method following a dependence of spill structure on the bandwidth.

QAR METHOD

The operational sequence of the QAR method is as follows: (1) the main parameters of synchrotron magnets are set so as to produce an original transverse separatrix under the third-order resonant condition, (2) particles are diffused by the RFKO just to the boundary of separatrix, (3) the separatrix size is shrunk with the excitation of a Fast Q magnet (FQ) to a certain size, and particles outside the separatrix are extracted, (4) the FQ is turned off, and (5) the above process is repeated until the entire circulating beam is extracted. The method has the following characteristics: 1) it can precisely extract particles prescribed at the required timing because the extraction period is controlled with only the FQ, and 2) it can reduce the cost of power supplies of main magnets because it does not require a very low current-ripple, such as the 10^{-6} order, by widening enough the original separatrix area than an emittance of circulating beam. A spill structure is controlled by a spill feedback operation using the FQ.

SPILL STRUCTURE DEPENDENCE ON THE BANDWIDTH OF COLORED NOISE

In Fig. 1(a) is shown a spill structure simulated with a bandwidth of 0.12 - 1.2 normalized by the revolution frequency of synchrotron. The simulation method is detailed in a previous paper [4]. The RFKO is operated continuously, and the FQ is not operated. The horizontal scale is the turn number, the vertical scale is particle number, and the numbers extracted during every 100 turns were plotted with the marks "•" which are connected with lines. The lattice of HIMAC synchrotron was used. The bandwidth is nearly equal to the value in the experiment of the QAR method with the HIMAC synchrotron, and includes two resonances of 1/3 and 2/3. It is found that the spill structure is not uniform. This shows that particles inside the separatrix are not diffused uniformly in spite of a bandwidth of colored noise wider than the betatron tune spread, 2/3 - 0.685.

A spill structure with a bandwidth widened to 4.7 is shown in Fig. 1(b), where the number of extracted particles is nearly the same as in the Fig.1(a). The unevenness was improved remarkably. The rms value of unevenness was as small as 0.37 for the same turn period. On the other hand, the unevenness was huge with a narrow bandwidth of 0.65 - 0.7 as shown in Fig. 1(c), in spite of the bandwidth wider than the tune spread of 2/3 - 0.685.

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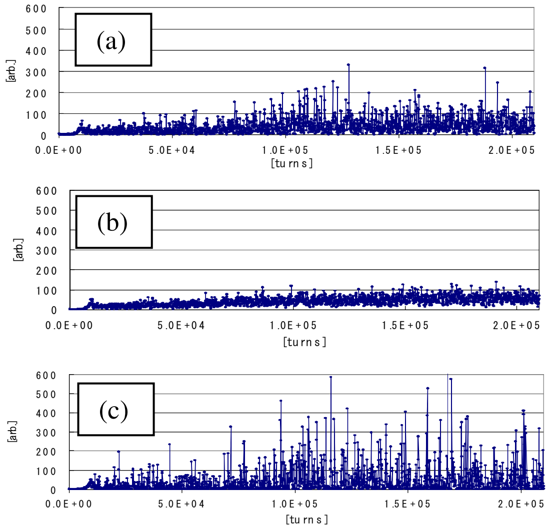

Figure 1: Spill structures with the bandwidths of 0.12-1.2 (a), 0.12-4.7 (b), and 0.65-0.7 (c).

COLORED NOISE WITH MULTI-BANDS

The wider bandwidth of colored noise signal gives the more uniform spill, but it requires a larger rf power of an amplifier. Contribution of frequency components outside the tune spread was studied to investigate the possibility of reduction of rf power of an amplifier. The result showed that frequency bands of only around n+1/3 and n+2/3 (n=0,1,2,・・・) are useful in a wide band colored noise, and other regions do not effectively contribute to diffuse the particles inside the separatrix [3]. An example of such a spectrum including many bands around the resonances is shown in Fig. 2(a). A total signal power to obtain a spill intensity is not dependent on the gross bandwidth, and is equal to that of colored noise with one band.

On the other hand, the multi-bands spectrum is useful to increase a spill intensity in the QAR method. The spill intensity is dependent on particle density around a separatrix boundary. The density becomes large with increasing the colored noise amplitude, but it is limited to a value that particles do not go outside the separatrix. An adjustment of the bandwidth of all bands makes the density large without diffusing particles just around the separatrix boundary. Figure 2(b) shows a result with norrmalized pass bands of $n+f_L$-$n+f_H$ and $n+(1-f_H)$-$n+(1-f_L)$ with f_L =0.678 and f_H =0.689 together with f_L =0.65 and f_H =0.7 covering the tune spread completely, where n=0, 1, 2, 3, 4. The extracted particles increased to about 10 times. A sawtooth wave for the FQ coil current was used and the shrink rate of the separatrix was 20 %.

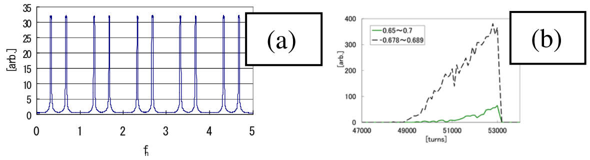

Figure 2: Multi-bands spectrum (a) and spill structures with different bandwidths (b).

BANDWIDTH AND AMPLITUDE OF THE MULTI-BANDS

Dependence of the spill on a bandwidth and an amplitude of the multi-bands spectrum are studied to extract particles more than 1 % of an accelerated beam. The used synchrotron lattice is one designed at NIRS for the carbon therapy facility [5]. The requirement is that the sum of particles extracted during the RFKO operation and ones in a separatrix area larger than 98 % of the original one is less than 0.1 % of each extracted particles. The 98 % means that variation of the separatrix area by ripple of the power supplies of main magnets is acceptable to 2 %. The number of bands is 10 (n=0-4), and f_H is fixed to 0.68 corresponding to the fractional part of the bare tune.

Simulations were done with 200,000 turns and 200,000 particles, where the separatrix was produced during the first 10,000 turns. Variation of spill intensities calculated is shown in Fig. 3, and spill structures enlarged around 100,000 turns are shown in Fig. 4 together with operation periods of the RFKO and the FQ.

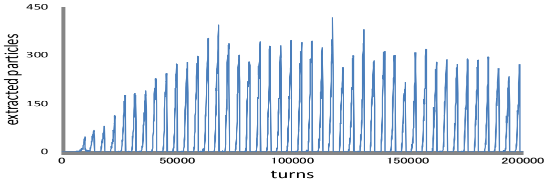

Figure 3: Spill variation.

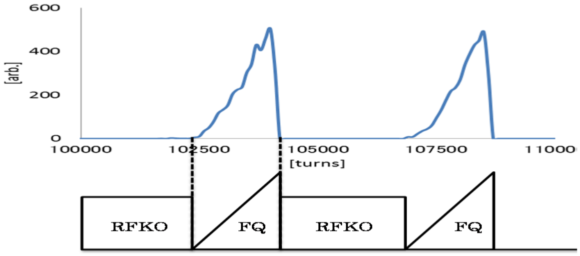

Figure 4: Spills and operation periods of RFKO and FQ.

Dependence of most extracted particles on f_L was calculated for a shrink rate of 15 %. It has a maximum value of 1.65 % at f_L = 0.676 which is shown in ratios to 200,000 particles and average values extracted between 50,000 and 200,000 turns . For a shrink rate of 20 %, it was 1.87 % at the same f_L, as shown in Table 1. Results when the extracted particles are decreased to around 1 % are also listed in Table 1. The amplitude of the multi-bands can be decreased to about one half. The extracted particles with the bands corresponding to the tune spread were 0.039 % at an relative amplitude of 0.6×10^{-5}.

Table 1: Average Extracted Particles Optimized

Shrink rate [%]	Extracted particles [%]	Relative amplitude	f_L
15	1.65	4.5E-05	0.676
15	1.07	2.4E-05	0.675
20	1.87	5.2E-05	0.676
20	1.06	2.2E-05	0.675

PRODUCTION OF MULTI-BANDS COLORED NOISE

An RF-knockout system for multi-bands is shown in Fig. 5. Band pass filters (BPFs) have frequency pass bands of around f_{rev}*(n+1/3) and f_{rev}*(n+2/3) (n=0,1,2,･･･), where f_{rev} is the revolution frequency of a synchrotron. A signal from a white noise source is divided, and they are fed to a power combiner through the BPFs. The combined signal is amplified and finally fed into the kicker electrode for the RFKO. The frequency pass bands for the first three BPFs are shown in the figure.

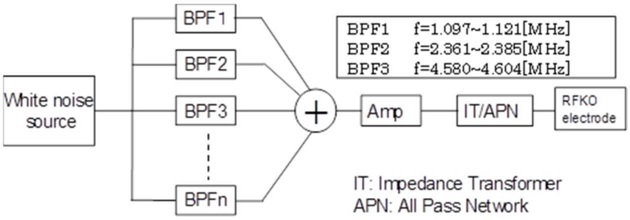

Figure 5: RFKO system with multi-bands colored noise.

PRELIMINARY EXPERIMENT

Production of the multi-bands colored noise was done preliminarily using a white noise source, a power combiner, and three BPFs shown in Fig. 5. A simple passive filter circuit for the BPFs shown in Fig. 6 was tried from availability. The R0 is an internal resistance of a generator and equal to R1 of 50 Ω. Calculated parameters of L and C are listed in Table 2, however real values were a little different for availability. Figure 7 shows a multi-bands spectrum obtained through the power combiner, where the last LC parallel circuits of the BPFs were removed because a signal level was very low owing to mismatch of the inductors and the capacitors. It is found that the spectrum with three bands was produced.

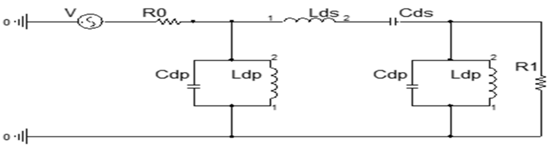

Figure 6: BPF circuit.

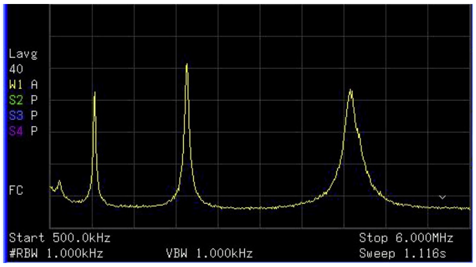

Figure 7: Multi-bands spectrum.

An active filter which consists of operational amplifiers, resistors, and capacitors would be better for the BPF, because the inductance for passive filter is very small for a higher band and adjustment of the inductors is very difficult.

Table 2: Parameters of BPFs

	BPF1	BPF2	BPF3
Lds [mH]	0.6631	0.6631	0.6631
Ldp [nH]	155.3	33.92	9.057
Cds [pF]	31.06	6.783	1.811
Cdp [μF]	0.1326	0.1326	0.1326

CONCLUSIONS

The uniform spill, or equivalently uniform diffusion requires a colored noise including frequency bands around many resonances of n+1/3 and n+2/3. Such a colored noise is useful to increase a spill intensity in the QAR method. The multi-bands colored noise was produced with the preliminary experiment using three BPFs.

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