RF-KNOCKOUT SLOW EXTRACTION DESIGN FOR XiPAF SYNCHROTRON

H. J. Yao, G. R. Li, Q. Zhang, S. X. Zheng†, X. L. Guan, X. W. Wang
Key Laboratory of Particle & Radiation Imaging (Tsinghua University), Ministry of Education, Beijing 100084, China
also at Laboratory For Advanced Radiation Sources and Application, Tsinghua University, Beijing 100084, China
also at Department of Engineering Physics, Tsinghua University, Beijing 100084, China

Abstract

The physics design of slow extraction for Xi'an Proton Application Facility (XiPAF) synchrotron is discussed. The extraction scheme is composed of two resonant sextupoles, one electrostatic septum (ES) and two septum magnets. The phase space diagram under the Hardt condition at the entrance of ES and the last three turn's trajectory before extraction are presented. A program is written with C++ to simulate slow extraction process by RF-knockout (RF-KO), the calculation results of dual frequency modulation (FM) and amplitude modulation (AM) are given, and the standard deviation of the fluctuation parameter R_1 can be limited 0.2 with optimum parameters under a sampling frequency of about 10 kHz.

INTRODUCTION

Xi'an Proton Application Facility (XiPAF) is under construction in Xi'an, China, to fulfil the need of the experimental simulation of the space radiation environment, especially for the research of the single event effect (SEE). XiPAF is mainly composed of a 7 MeV linac injector, a synchrotron (60~230 MeV) and two experimental stations. The synchrotron [1] has a 6-fold "Missing-dipole" FO-DO lattice with its circumference of 30.9 m. The irradiation experiments require 1~10 s proton beam, so the slow extraction system has been designed for XiPAF synchrotron. For this facility, the third-integer resonance and RF-KO (Radio Frequency Knock Out) technology are applied to accomplish slow extraction. The parameters of XiPAF synchrotron related to slow extraction system are listed in Table 1.

Table 1: The Parameters of XiPAF Synchrotron

Parameter	Value	Unit
Injection energy	7	MeV
Extraction energy	60~230	MeV
Circumference	30.9	m
Maximum repetition rate	0.5	Hz
Maximum β_x/β_y	5.8/6.0	
Extraction υ_x/υ_y	1.678/1.794	

EXTRACTION SYSTEM SCHEME

The scheme of extraction system for XiPAF synchrotron is shown in Fig.1, the extraction elements consist of four sextupoles (SR1, SR2, SC1, SC2), one electrostatic wire septum (ES), two septum magnets (MS1, MS2) and one RF-KO kicker. As showed in Fig. 1, one pair sextupole magnets SR1 and SR2 are used for resonance excitation. The phase advance between SR1 and SR2 is about 5π/3, and they have same strength but opposite sign., which leads to the same function on resonance but cancellation of the chromaticity correction Another pair sextupole magnets SC1 and SC2 are used for chromaticity correction. The phase advance between SC1 and SC2 is also about 5π/3, and they have same strength and same sign, which leads to the same function on chromaticity without affecting the resonance.

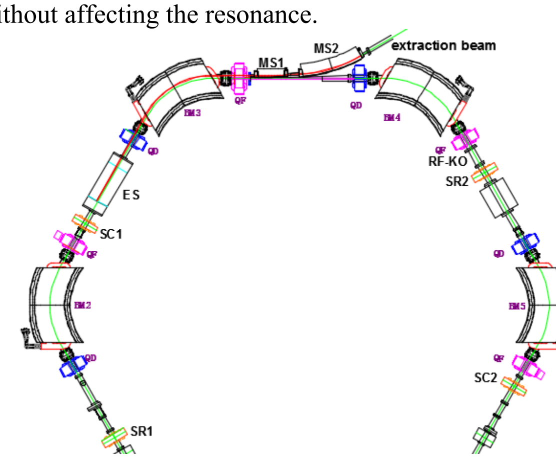

Figure 1: The extraction system scheme for XiPAF synchrotron.

The ES is used to give a kick to the particles entering the ES gap by the electrostatic field in order to separate from the circulating beam remaining inside the separatrix. In addition, two septum magnets MS1 and MS2 are used to deflected beam toward the beam transport line for extraction. The main parameters of ES, MS1 and MS2 are listed in Table 2.

Table 2: Main Parameters of ES, MS1 and MS2

Parameter	ES	MS1	MS2
Kick angle (mrad)	11	87.3	453.8
Max. magnetic field (T)	/	0.34	081
Max. electric field (MV/m)	5.7	/	/
Effective length (m)	0.8	0.6	1.3
Septum thickness (mm)	0.1	15	30

The ES is closed to the focusing quadrupole where the beta function has large value, and the phase advance between ES and MS1 is 92 degrees. Based on the formula (1), a large horizontal deflection will be obtained at the septum magnet MS1, which makes the design of MS1 easier.

† zhengsx@tsinghua.edu.cn

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$$\Delta x = \theta \sqrt{\beta_{ES} \beta_{MS}} \sin \mu . \qquad (1)$$

Where θ is the kicker angle of ES, β_{ES} and β_{MS} are beta function values at ES and MS1 respectively, μ is the phase advance between ES and septum magnet MS1.

TRACKING SIMULATION

Computer simulations of third-integer resonance extraction has been performed using MAD-X [2] code, the horizontal tune is chosen at 5/3. Figure 2 shows the phase space distributions at the entrance of the ES (a), the exit of ES (c) and the entrance of the first septum magnet MS1 (d). The Fig.2 (b) is the local zoomed graph of (a). From this figure, we can see that only one separatrix is crossed with the septum of ES, the normalized sextupole strength is 35 $m^{-1/2}$, and the spiral step is 5 mm as shown in Fig.2 (b).

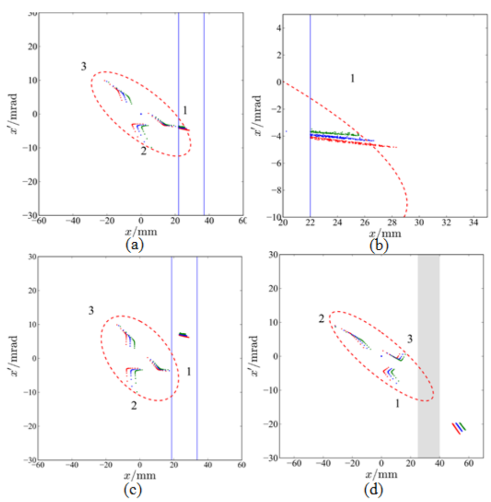

Figure 2: The phase space distributions at three different positions: the entrance of ES (a), the exit of ES (c), the entrance of MS1 (d), (b) is the local zoom of (a).

The ES is located in the descending part of the dispersion to fulfil the Hardt condition [3]. At the entrance of ES, $D_n \approx 1.2\ m^{0.5}$, $D_n' \approx 0.45\ m^{0.5}$, when the chromaticity value is -0.7, the Hardt condition is fulfilled. Figure 3 shows the separatrix at the entrance of ES under three different momentum spread -0.1% (red), 0 (blue), and 0.1% (green). It is apparent that the separatrix of extraction for three conditions are overlapping, which means the Hardt condition is fulfilled very well.

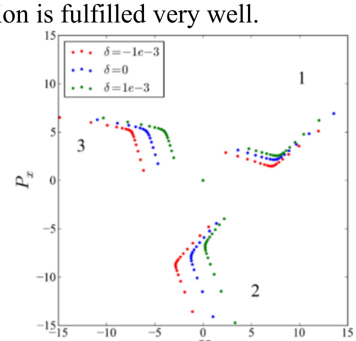

Figure 3: The separatrix under three momentum spread and with the Hardt condition fulfilled.

We calculated the trajectories of last three turns of the particle with the maximum spiral step before it enters the electrostatic septum, and the extraction trajectory together, which are shown in Fig.4. The original point of the trajectories is the entrance of ES. The maximum position of the extraction trajectory appears at the focusing quadrupole between ES and MS1, so a large bore quadrupole is used at this position.

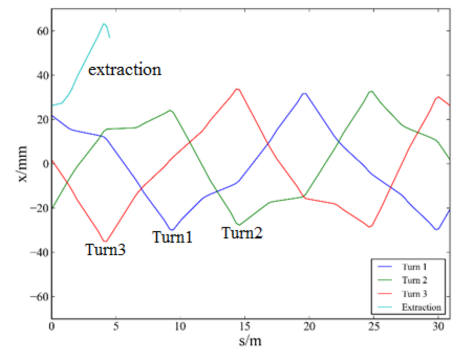

Figure 4: The last three turns before entering the electrostatic septum and the extraction trajectory.

RF-KNOCK OUT

For XiPAF, the RF-Knock Out slow extraction method is used to obtain the beam current for 1~10 s. The circulating particles continue to be extracted from the inside of the separatrix to its outside by using the constant separatrix and transverse RF field. To have a perturbation resonant with the particle, the frequency of the transverse RF field should be matched with that of the betatron oscillation.

A C++ code Li-Tracker is written to simulate the RF-KO slow extraction process, which including all kinds of elements in XiPAF synchrotron, and it's a multi-particles tracking program. Due to the limitation of calculation time, in our simulation the extraction time 0.01 s has been used for the calculation, it is about 60000 turns. The phase space distribution is shown in Fig.5, 18000 particles and 60000 turns are used in this simulation. From the turn 0 the sextupoles SR1 and SR2 are ramped linearly in 6000 turns; and then the RF-KO is turned on in the next 54000 turns while the magnetic elements keep constant.

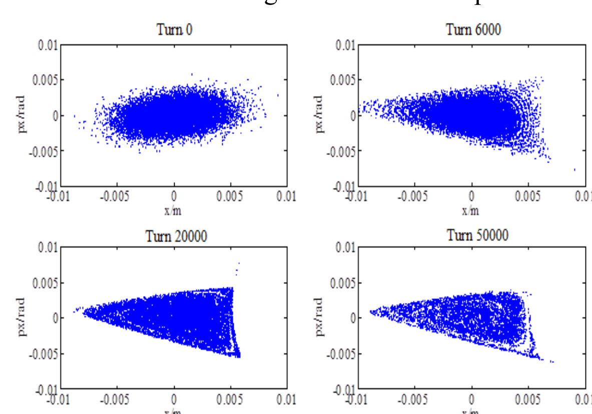

Figure 5: The phase distribution during extraction.

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For the RF-KO slow extraction method, the parameters of frequency modulation (FM) and amplitude modulation (AM) are very important. In our calculations, the dual FM method as described in Ref [4] and AM function in Ref [5] are used in order to make the extraction spill more uniform. The optimized parameters including the center frequency, the bandwidth, the AM parameters and so on, have been obtained and listed in Table 3.

Table 3: The Optimized Parameters of Dual FM and AM

Parameter	Value	Vale
Extraction energy (MeV)	60	230
Center frequency (MHz)	2.24	3.91
Bandwidth (kHz)	22	37
Repetition frequency (kHz)	5	5
AM parameter r_0^2	50×10^{-6}	32×10^{-6}
AM parameter σ_0^2	32×10^{-6}	6×10^{-6}
τ_{prac}/τ_{ext}	1.25	1.25
R_1	±17%	±20%

The 230 MeV, 0.01 s extraction spill structure and the FFT result are shown in Fig.6 under a sampling frequency of about 10 kHz. From the FFT result, we can observe the peak due to the RF-KO. In our calculations the synchrotron oscillation has not considered. In order to characterize the spill structure and to compare it, one parameter R_1, the standard deviation of the fluctuation from the analytical estimation is defined in Ref [5]. The results of R_1 is also listed in Table 3. The value of R_1 is smaller, which means that the spill is more uniform.

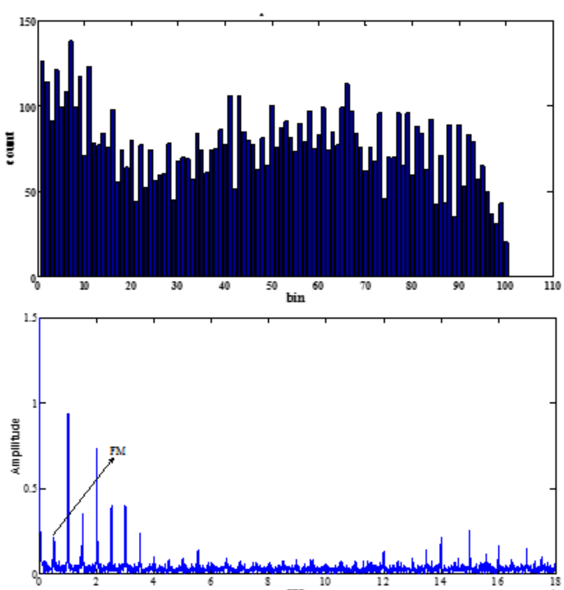

Figure 6: The extraction spill structure and FFT result.

The kick angle with the turn number is shown in Fig.7; from the figure we can see that the maximum kick angle is about 6 μrad for the extraction duration of 0.01 s and the extraction energy of 230MeV, then maximum kick angle needed for extraction time of 1 s and extraction energy of 60MeV can be derived, which is 1.1 μrad, and is 1.4 μrad for 7 MeV. With margin, 2 μrad is used for the kicker voltage calculation. A pair of plate electrodes is employed as the RF kicker, the electrodes gap is 0.11 m and the length is 0.3 m, the peak-peak voltage value is ±215 V.

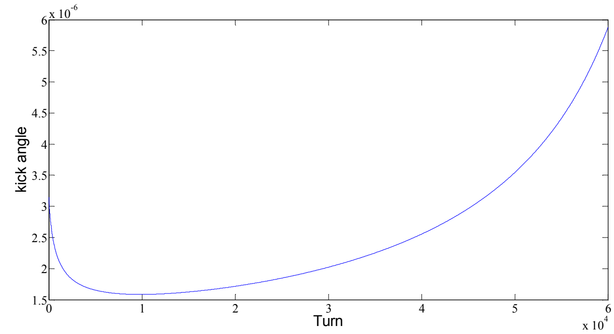

Figure 7: The kick angle vs turn number.

CONCLUSION

The third integer slow extraction with RF-KO method for XiPAF synchrotron has been described. The tracking simulation of the 3rd order resonance is done with MAD-X code, and the extraction process with RF-KO method is simulated with Li-Tracker code, and the main parameters of electrostatic septum, septum magnets, FM, AM and kicker electrodes have been listed in this paper. The parameter R_1 is ±20% for 60~230 MeV under a sampling frequency of about 10 kHz, which meets the requirement of the experimental stations.

At present, the block diagram of the RF-KO system with a complicated feedback system has been designed to keep the extracted beam current more stable, and the Code Li-Tracker is improving with the synchrotron oscillation and space charge effect are taken into account, we will report the new development in the future.

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