STUDY OF ACHIEVING LOW ENERGY BEAM BY ENERGY DEGRADATION AND DIRECT RESONANCE EXTRACTION IN A COMPACT RING

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Abstract

We have designed a compact proton synchrotron (7~230 MeV) for applications like proton therapy and space environment study. These applications require slow extraction from 10~230 MeV. Traditionally, the low energy beam (10~60 MeV) is achieved by energy degradation from high energy beam which may cause beam lose and energy spread increase, because the beam quality may suffer from magnetic remanence, power ripple and strong space charge effects in low energy stage. To achieve high quality beam directly from resonance extraction, we study these effects by multi-particle simulation. Methods of improving beam quality are discussed.

INTRODUCTION

Xi'an Proton Application Facility (XiPAF), under construction in Xi'an, China, is dedicated to radiation applications like proton therapy, single event effects (SEE) study [1]. XiPAF's accelerator complex is composed of a 7 MeV Linac, a synchrotron (7~230 MeV) and two beam lines. For many radiation applications, slow extraction from synchrotron is required. For this facility, we accomplish slow extraction by applying 3rd order resonance and RF-KO technology [2]. Usually, the extraction energy of a synchrotron does not fully cover the low energy region. For the first stage consideration, the lowest extraction energy of 60 MeV is allowed. But beam energy of 10~60 MeV is also of interesting for some applications. The beam quality of resonance slow extraction may be strongly affected by the worse magnetic field quality and larger power ripple when magnetic field is lower. In low energy stage, strong space charge effect would cause strong incoherent tune shift, which would obviously affect the slow extraction process based on resonance and RF-KO. So traditionally, the low energy beam is achieved by an energy degrader. But this would cause radiation pollution and enlarge the energy spread. In this study, we try both methods of achieving low energy beam by energy degradation and direct resonance extraction. The parameters of the synchrotron related to this topic are listed in Table. 1.

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Table 1: Parameters of XiPAF's Synchrotron

Parameter	Value	Unit
Injection Energy	7	MeV
Extraction Energy	60(10)~230	MeV
Maximum Intensity	2×10^{11}	ppp
Circumference	30.9	m
Dipole Field	0.25~1.52	T
Maximum β_x/β_y	5.8/6.0	m
Extraction ν_x/ν_y	1.678/1.794	

LOW ENERGY BEAM BY DEGRADATION

Energy degrader is widely used in cyclotron based facility. Beam energy can be varied easily by penetrating beam through a variable thickness rangeshifter. The benefit of an energy degrader is no need for setting change of accelerator. However, the energy degrader would cause beam energy straggling and emittance growth due to discrete stochastic energy loss and multiple Coulomb scattering. Thus for a real application beam line, energy degrader is usually followed by a bending magnet and a collimator slit to select beam with required energy precision. This energy selection process will significantly reduce the beam intensity.

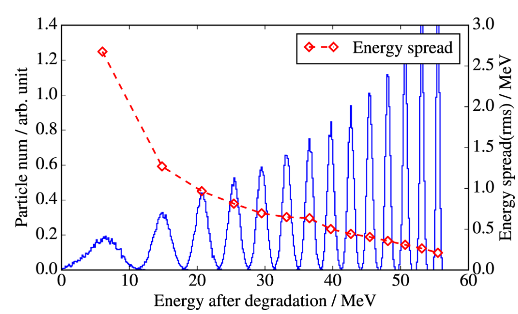

Figure 1: Beam energy distribution after penetrating a degrader. Red dashed line indicates the energy spread.

We plan to achieve low energy beam from 60 MeV beam. The penetration process is simulated by SRIM [3]. Considering the small energy spread of beam directly extracted from synchrotron, the incident beam is set to have an initial rms energy spread of ±0.03 MeV. The material of degrader is

Carbon. Beam energy distribution after penetrating different length of Carbon core is shown in Fig. 1.

The simulation result shows that the energy straggling grows rapidly with the increasing of energy degradation. When beam energy is below 30 MeV, the energy spread will reach several MeV, comparable to its mean energy. The survival rate of beam after energy selection is defined as the ratio of particles whose energy locate in $(E_{\rm mean} - E_{\rm lim}, E_{\rm mean} + E_{\rm lim})$, where $E_{\rm mean}$ is mean energy of beam and $E_{\rm lim}$ is the energy spread limit. Beam survival with different $E_{\rm lim}$ is shown in Fig. 2. When required energy precision is high, like ±0.1 MeV, the survival rate would significantly reduce to below 5% after $E_{\rm mean}$ is below 30 MeV. As the design maximum intensity is around 2×10^{11} ppp for XiPAF's synchrotron, the remaining intensity would be below 1×10^{10}. Thus direct low energy extraction becomes very attractive for our project.

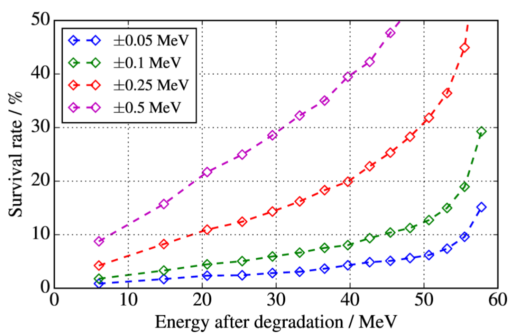

Figure 2: Beam survival rate with different energy selection precision.

DIRECT SLOW EXTRACTION

There are some factors that may affect the extraction in low energy stage. The uniformity of magnetic field becomes worse due to magnetic remanence. The power ripple may be stronger than normal state. What's more, the tune shift can't be neglected if relative high beam intensity is also required.

Magnetic Remanence

Previous clinical synchrotron operation experience shows low energy extraction down to 17 MeV is possible [4]. For this project, the magnetic field at injection energy (7 MeV) is about 0.25 T, much larger than remanence field (several Gauss). Thus we speculate that magnetic remanence would not be the dominated factor for direct extraction over 7 MeV. The main problem is the nonlinear field introduced by remanence, which may take effect with the strong tune spread and cause emittance growth or beam lose. This subject should be further investigated with measured magnetic field map and particle tracking.

Power Ripple

Power ripple of quadrupole will change the acceptance of separatrix, causing beam ripple. We study this phenomenon by introducing coherent sinusoidal ripple for each quadrupole in our simulation model. Cases of different ripple amplitude and period are studied. Typical time structure of spill with power ripple are shown in Fig. 3.

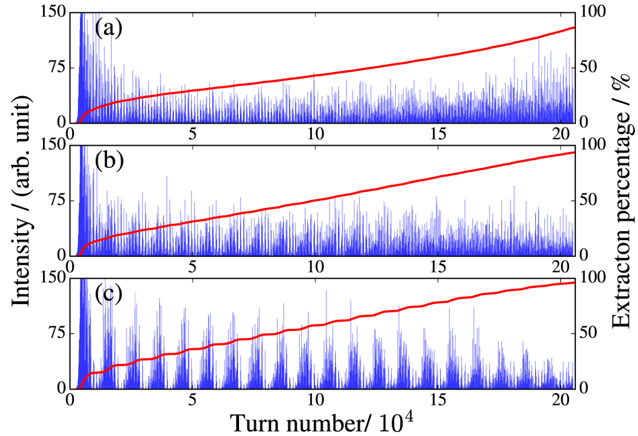

Figure 3: Time structure of spill. The ripple period of quadrupole strength is 10000 turns. The ripple amplitude of quadrupole strength is (a) 1×10^{-4}, (b) 2×10^{-4} and (c) 5×10^{-4}.

The level of beam ripple is characterized by the ratio of beam intensity's standard deviation to mean. In Fig. 4, we present the results of different simulation cases. Beam ripple is not significantly affected by power ripple until the power ripple reaches 5×10^{-4}. Spill is more sensitive to high frequency power ripple. Thus we draw 5×10^{-4} as a threshold of power ripple for full extraction energy range of 10~230 MeV. Compensating bare tune ripple by fast quadrupole is also under consideration.

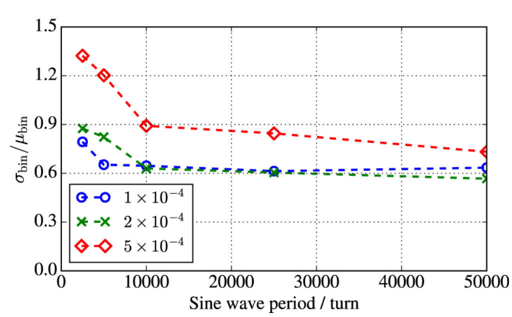

Figure 4: The level of beam ripple of different simulation cases.

Space Charge Effect

Slow extraction based on resonance and RF-KO is highly sensitive to the betatron tune. When beam energy is low, strong space charge will cause tune shift, thus it will affect the extraction process. We study this process by multi-particle simulation. The space charge effect is expressed as a kick for each particle. As particle distribution can be highly chaotic when resonance and transverse rf kick are applied, we calculate space charge kick from the real distribution by solving Possion equation. We apply a fast algorithm to solve

ISBN 978-3-95450-147-2

Possion equation as described in Ref. [5]. The step length of space charge kick calculation is about 0.2 m, a small step to reflect the oscillation of beta function.

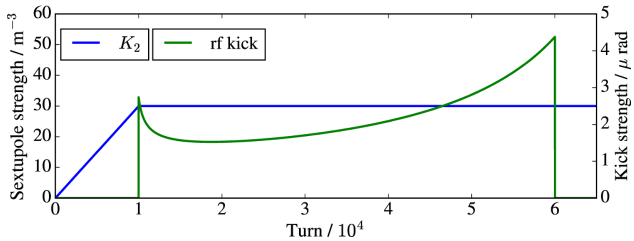

Figure 5: Work mode of sextupole and RF-KO.

As shown in Fig. 5, the extraction process is divided into two stages: (1) Sextupole is ramped linearly in 10000 turns without RF-KO and then (2) RF-KO is on in the next 50000 turns while magnetic elements keep constant. The kick strength of RF-KO is tuned with time to make extraction more uniform as described in Ref. [6]. Two extraction cases of 30 MeV beam energy are studied. Their beam intensity are 1×10^{10} and 4×10^{10}. The initial tune spread is shown in Fig. 6.

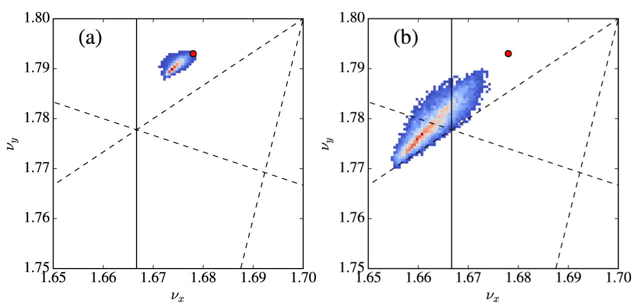

Figure 6: Initial tune spread when beam energy is 30 MeV and beam intensity are (a) 1×10^{10}, (b) 4×10^{10}. Red dot indicates the bare tune of the ring.

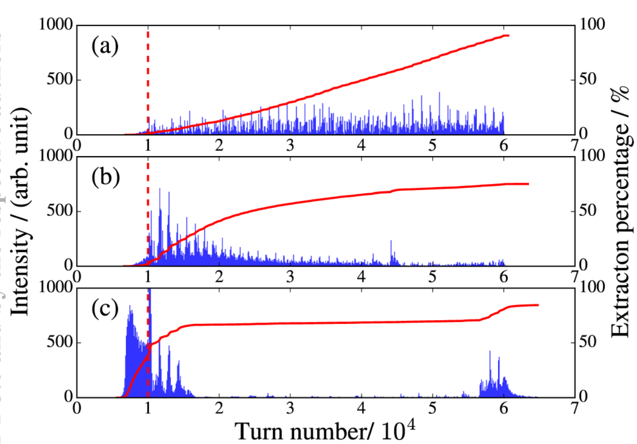

Figure 7: Time structure of spill. Red solid line indicates the extraction percentage. Beam intensity are (a) 1×10^9, (b) 1×10^{10} and (c) 4×10^{10}.

The time structure of spills are shown in Fig. 7. We take a low intensity case (Fig. 7 (a)) as a reference. For 4×10^{10} beam intensity case, over 40% of beam is lost during the ramping of sextupole. After the ramping process, the beam profile becomes super non-uniform compared with the low intensity case. For 1×10^{10} beam intensity case, as its tune shift dose not cross the $\nu_x = 5/3$ resonance line, the lose rate during sextupole ramping is acceptable. However, its time structure has also been influenced by tune spread. More extraction events arise during the earlier turns.

Direct extraction of 1×10^{10} particles is comparable with the result achieved by energy degradation when required energy precision is below ± 0.1 MeV. As the losing mechanism is dominated by resonance line crossing, a larger separation of bare tune from 5/3 seems a possible way to improve the intensity of direct extraction. Further study should be devoted to the simulation of different work point and methods to improve time uniformity with strong space charge effect.

CONCLUSION

In this paper, we present the preliminary study results of achieving low energy beam by energy degradation and direct slow extraction. The degradation method is easy to realize but introduces strong energy straggling. The beam intensity will be less than 5% of initial intensity if beam energy is below 30 MeV and required energy precision is below ± 0.1 MeV. Different factors relative to direct extraction include magnetic remanence, power ripple and space charge effect are considered. The simulation results shows direct extraction is possible to reach a similar intensity compared with degradation method. More elaborate study is need to reveal the intensity potential. Methods of making spill more stable with strong space charge should be investigated.

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ISBN 978-3-95450-147-2