SIMULATION AND EXPERIMENT OF LOW-ENERGY SLOW EXTRACTION AT XiPAF

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Abstract
Extraction by third order resonance in low-energy stage suffers from strong space charge effect, high beam emittance, high power ripple and so on. Low-energy slow extraction at 10 MeV has been explored theoretically and experimentally at synchrotron of Xi’an Proton Application Facility (XiPAF), which is a compact synchrotron with injection energy of 7 MeV and extraction energy up to 230 MeV [1]. In this paper, simulation and experimental results of slow extraction of 10 MeV intense beam are presented. By using high-order harmonic excitation, the RF-KO slow extraction below resonance is the optimal scheme for slow extraction in low-energy stage with strong space charge effect.

INTRODUCTION
Beam energy range of 10–60MeV is of interest and in great demand for XiPAF. Achieving low energy beam by energy degradation and direct slow extraction has been analysed in detail in G.R. Li’s work [2]. Strong space charge effect is the main reason limiting extraction rate and time uniformity of extracted beam spill. In spite of this, low-energy slow extraction can achieve higher efficiency and better beam quality than energy degradation.

Third order resonance slow extraction by RF-KO has been adopted in XiPAF synchrotron. Table 1 shows parameters of XiPAF synchrotron.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection energy</td>
<td>7</td>
<td>MeV</td>
</tr>
<tr>
<td>Extraction energy</td>
<td>10–230</td>
<td>MeV</td>
</tr>
<tr>
<td>Maximum Intensity</td>
<td>2 × 10^{11}</td>
<td>ppb</td>
</tr>
<tr>
<td>Circumference</td>
<td>30.9</td>
<td>m</td>
</tr>
<tr>
<td>Maximum β_{x}/β_{y}</td>
<td>5.7/6.0</td>
<td>m</td>
</tr>
<tr>
<td>Chromaticity ξ_{x}/ξ_{y}</td>
<td>-0.21/-2.27</td>
<td></td>
</tr>
<tr>
<td>Extraction v_{x}/v_{y}</td>
<td>1.678/1.765</td>
<td></td>
</tr>
</tbody>
</table>

Further research on third order resonance slow extraction in low-energy stage of proton synchrotron has been carried out at XiPAF in three aspects, including theoretical analysis of the influence of space charge effect on slow extraction, design of low-energy slow extraction schemes and low-energy slow extraction experimental research.

INFLUENCE OF SPACE CHARGE ON SLOW EXTRACTION

In low-energy stage of intense proton synchrotron, strong space charge effect would cause big incoherent tune shift, which would obviously affect the slow extraction process based on third order resonance and RF-KO. The influence of space charge on slow extraction can be analysed from the following two aspects.

Resonance Crossing
The horizontal extraction tune is 1.678 for nominal design of XiPAF synchrotron, beam would cross third order resonance and be lost before extraction due to distributed sextupolar error when maximum incoherent tune shift caused by space charge exceeds ~0.011, corresponding to beam intensity of around 2 × 10^{10} per bunch at energy of 10 MeV. Two solutions are possible to resolve this problem. One is reducing the intensity of injected beam so that the number of particles after acceleration does not exceed the limit value. Another one is choosing a appreciate tune below third order resonance during injection, acceleration and extraction. The latter one is obviously better because of unlimited beam intensity.

Beam Excitation
As for slow extraction based on RF-KO, beam excitation by transverse RF signal is a key process during extraction. As the RMS emittance of the beam grows during RF-KO excitation, oscillation of beam centroid which is pernicious for slow extraction will also be excited. We established a theoretical model of beam excitation with linear space charge, which is applicable to moderate space charge. Theoretical model and simulation results both show that when a beam with strong space charge effect is excited by a coloured noise, the beam mainly exhibits coherent oscillation with large amplitude, while the RMS emittance hardly grows. We can explain this phenomenon as follows. Direct space charge effect can only cause incoherent tune shift, while coherent tune of beam remains unchanged. As for low-energy intense beam, coherent tune of beam differs from centre of incoherent tune spread, so that transfer of energy from coherent to incoherent motion is suppressed. The consequence is that the extraction rate and time...
uniformity of extracted beam spill decrease as the space charge effect increases, as we can see in G.R. Li’s work [2].

In order to increase RMS emittance growth rate during RF-KO excitation and suppress coherent oscillation, we need to increase incoherent tune spread, so that more incoherent particle tune lies around coherent tune. A method to increase incoherent tune spread seen by RF-KO, and then to reduce the influence of space charge effect by using high-order harmonic excitation is proposed. Due to energy spread of beam, the revolution period is energy-related, and the incoherent tune spread seen by RF-KO caused by energy spread is:

\[
\Delta v_k = \left[-(k-q)\eta - \xi_x\right] \delta, k > 0 \\
\Delta v_k^* = \left[-(k+q)\eta + \xi_x\right] \delta, k \geq 0
\] (1)

Where q is decimal part of bare tune, \(\xi_x\) is horizontal chromaticity, \(\eta\) is phase slip factor, \(\delta\) is momentum spread, \(k\) is harmonic number, superscript minus means lower sideband, and superscript plus means upper sideband. The item in square brackets is also called “effective chromaticity” [3]. From Eq. (1), we can see that effective chromaticity increase with harmonic number \(k\) when \(k\) is big enough.

**SIMULATION RESULTS**

*Simulation Code*

A PIC code with 3D space charge effect called SynTrack is developed in Tsinghua University. 3D poison solver based on integrated Green’s function method [4] is adopted in SynTrack, which supports free and longitudinal periodic boundary conditions, and can simulate 3D space charge force of beams with large aspect ratios accurately.

*Extraction Schemes*

As for extraction above third order resonance, beam intensity before extraction is limited by tune distance and space charge incoherent tune shift. Apart from this, for the sake of high emittance of low-energy beam and characteristic of space charge that incoherent tune of beam core is closer to resonance, most of particles will be lost or extracted during ramping of sextupoles. Just as we can see from the results of nominal extraction scheme in Fig. 1(a), where sextupoles are turned on and ramped linearly in 5000 turns without RF-KO and then RF-KO is on in the next 30000 turns while magnetic elements keep constant.

According to analysis above, we proposed two extraction schemes dedicated for low-energy slow extraction:

- Extraction above third order resonance, slowly shrink stable triangle by slowly ramping sextupoles or by slowly moving tune towards third order resonance, when the stable triangle is small enough, turn on RF-KO.
- Extraction below third order resonance, extract beam by RF-KO.

The simulation results of extraction schemes above third order resonance are shown in Fig 1. Three schemes are simulated and compared. As we can see from Fig 1, the uniformity of extracted beam spill is improved by slowly shrinking the stable triangle. Due to limited tune distance from resonance and negative incoherent tune shift, beam intensity before extraction is limited about \(2 \times 10^{10}\). But if we shrink the triangle by moving tune towards resonance, a bigger initial tune distance can be selected, and beam intensity before extraction can be further expanded to \(4 \times 10^{10}\).

![Figure 1](image.png)

**Figure 1**: Time structure of spill. Red solid line indicates the extraction percentage. Orange solid line indicates beam intensity percent remains in the ring. (a) nominal extraction scheme, beam intensity is \(1 \times 10^{10}\). (b) Sextupoles are slowly ramped in 30000 turns, and RF-KO is turned on since 15000 turns, beam intensity is \(1 \times 10^{10}\). (c) Sextupoles are ramped in 5000 turns, horizontal tune is tuned linearly from 1.7 to 1.68 in 20000 turns, and RF-KO is turned on since 20000 turns, beam intensity is \(4 \times 10^{10}\).

The simulation results of extraction schemes below third order resonance are shown in Fig 2. The transverse working point of ring is optimised and tuned to \((1.663,1.633)\). High-order harmonic and lower sideband excitation are adopted according to Eq. (1). Limited by the frequency range of the RF-KO power source, excitation tune of 4.337 is chosen. Just the same as nominal extraction scheme, sextupoles are turned on and ramped linearly in 5000 turns without RF-KO and then RF-KO is on in the next 30000 turns while magnetic elements keep constant.

As we can see from Fig 2, extraction rate and time uniformity of extracted beam spill are much better than that of schemes above resonance, even when beam intensity reaches \(1 \times 10^{11}\), and the corresponding maximum space charge incoherent tune shift is \(-0.07\). Besides, when the maximum incoherent tune shift of the coasting beam exceeds \(-0.1\), harmonic number over 20 can completely suppress the inhibition effect of space charge on RMS emittance growth. So, the beam intensity can be further increased if we use higher order harmonic number.

We can summarise the advantages of extraction scheme below resonance as follows:
• The beam intensity before extraction is not limited.
• The proportion of particles extracted during ramping of sextupoles is much lower than that of schemes above resonance, and decrease with increasing beam intensity. Therefore, there is no need to optimise sextupole or quadrupole curves to optimise uniformity of spill.
• With the help of high-order harmonic excitation, the uniformity of spill is completely controlled by RF-KO, and can be optimised using RF-KO amplitude feedback.

RF-KO is turned on since 450 ms. Total extraction rate within 300–1300 ms is 69%. Uniformity of spill is much better than of schemes above resonance, and can be further improved by RF-KO amplitude feedback. Slow extraction as well as beam instabilities excited by RF-KO with strong space charge were studied in detail at beam intensity around $9 \times 10^{10}$ ppb, corresponding to maximum incoherent tune shift around $-0.06$.

**EXPERIMENTAL RESULTS**

Experiments of 10MeV slow extraction have been conducted at XiPAF synchrotron, and desired results have been achieved.

*Above Resonance*

Shrinking stable triangle by slowly ramping sextupoles has been adopted in experiment, and the typical result of extraction is shown in Fig 3. The sextupoles ramp slowly in an optimised way from 300 ms to 1200 ms. RF-KO is turned on since 1000 ms. Total extraction rate within 300–1300 ms is 39%. Due to limited beam intensity before extraction, the maximum intensity of extracted beam spill is $1.5 \times 10^{10}$.

*Below Resonance*

Typical result of extraction below resonance is shown in Fig 4. The sextupoles ramp rapidly from 300 ms to 325 ms.}

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Figure 2: Time structure of spill. Red solid line indicates the extraction percentage. Orange solid line indicates beam intensity percent remains in the ring. Excitation tune of RF-KO is 4.337. Beam intensities are (a) $2 \times 10^{10}$, (b) $6 \times 10^{10}$, (c) $1 \times 10^{11}$.

According to simulation results and advantages list above, we can conclude that the RF-KO slow extraction below resonance is the optimal scheme for slow extraction in low-energy stage with strong space charge effect.

Figure 3: Extraction results of extraction scheme above resonance. Blue line indicates the intensity in the ring measured by DCCT. Brown line indicates extracted beam spill measured by iron chamber. Red line indicates extraction rate.

Figure 4: Extraction results of extraction scheme below resonance. Blue line indicates the intensity in the ring measured by DCCT. Brown line indicates extracted beam spill measured by iron chamber. Red line indicates extraction rate.

**CONCLUSION**

In this paper, we present research results on third order resonance slow extraction in low-energy stage of proton synchrotron. We proposed a new method to promote RMS emittance growth as well as to suppress coherent motion of beam with strong space charge by using high-order harmonic excitation. With the help of high-order harmonic excitation, the RF-KO slow extraction below resonance is the optimal scheme for slow extraction in low-energy stage with strong space charge effect. We also verified conclusions above by 10 MeV slow extraction conducted at XiPAF synchrotron. Quasi-uniform spill and extraction rate around 65% were achieved under the condition that maximum incoherent tune shift reaches $-0.06$. 
REFERENCES


