ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: https://doi.org/10.18429/JACoW-IPAC-23-TUPM138

OPTIMIZATION OF LOW-ENERGY SLOW EXTRACTION EFFICIENCY OF XiPAF*

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Abstract

Xi'an Proton Application Facility (XiPAF) synchrotron provides 10~200MeV proton beam for the experimental simulation of the space radiation environment. Due to the space charge effect, the slow extraction of 10 MeV proton beam is a work full of challenges. In a past experiment, the total extraction efficiency was over 65% with 4.5 ~ 6.5×10^{10} protons stored before extraction but decreased to 52% with 9×10^{10} protons stored. In order to study the beam loss caused by a strong space charge effect, based on experimental parameters, the beam loss fractions at different positions of XiPAF synchrotron are obtained through the simulation. According to the beam loss analysis, optimized parameters are found for reference in subsequent experiments. It is also noted that negative beam average momentum spread before extraction is beneficial to the improvement of extraction efficiency.

INTRODUCTION

Xi'an Proton 200 MeV Application Facility (XiPAF) is dedicated to simulations of the space radiation environment. It consists of a 7 MeV linac injector and a compact synchrotron [1]. The XiPAF synchrotron is a 10-200 MeV proton ring of 30.9 m circumference.

During irradiation, the beam is slowly and continuously extracted by third-order resonance slow extraction. It is performed by setting the horizontal machine tune close to the third-order resonance which for XiPAF is 5/3 and turning on the resonant sextupole magnets (SR) [2]. Then the particles are driven to leave the stable triangle phase-space excited by transverse radiofrequency (RF) field [3] and extracted by the electrostatic septum (ES) and magnetic septa (MS).

In the low-energy slow extraction, the space charge effect is not negligible. It causes the incoherent and coherent tune shift of the beam and even an incoherent tune spread when the beam traverse distribution is not uniform [4].

The maximum incoherent tune shift for 9×10^{10} 10 MeV protons is about -0.06 while the tune distance to resonance of normal slow extraction is about 0.014 (1.680-5/3). Another influence of space charge on slow extraction is that it is more difficult to excite particles to leave the stable triangle phase-space by transverse RF [5, 6].

In a past 10 MeV proton beam extraction experiment, the total extraction efficiency was over 65% with 4.5×10^{10} ~ 6.5×10^{10} particles stored before extraction by setting the horizontal tune below the third-order resonance (5/3) and using a high multiple-frequency radiofrequency knock-out (RFKO) signal. But when the number of particles stored before extraction was increased to 9×10^{10}, the total extraction efficiency was reduced to about 52% [5].

Due to the lack of beam loss detectors, it is not possible to know the specific position of the beam loss in the synchrotron, so corresponding optimization methods are hard to find. Therefore, the reduced extraction efficiency caused by the space charge effect is studied by simulations in this paper providing an optimal direction for the next beam commissioning to achieve high extraction efficiency.

METHOD

The extraction process is simulated by Syntrack [5] which is developed based on Li-track [7] with more functions and better usability. The Syntrack code is a parallel multiparticle tracking program written entirely in C++, thus can achieve a high computational speed.

Syntrack is also a PIC (Particle-In-Cell) program that includes a 3D space charge force algorithm. The space charge force algorithm is based on the integrated Green's function method [8] and supports free boundary conditions and longitudinal periodic boundary conditions. It can accurately simulate the 3D space charge force of a large aspect ratio beam.

Considering that the acceptances at bending magnets, ES and MS are relatively small in XIPAF, aperture elements are only placed at the entrance and exit of such elements to simplify the loss calculation.

To simplify the loss definitions at different elements, we define the number of the particles lost before turning on the RFKO as n_{bf} and the number of the particles lost during the RFKO extraction process as n_{rf}. The n_{rf} can be further divided into the amount of the particles extracted to the transport line n_{ex}, the particles lost in the extraction channel (a channel starting from ES entrance and ending at the MS entrance) n_{ec}, the particles lost at the ES of the circulating beam n_{ESc}, the particles lost at the bending magnets of the circulating beam n_{sb} and the particles lost at MS of the circulating beam n_{ms}.

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ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: https://doi.org/10.18429/JACoW-IPAC-23-TUPM138

With the definition above, the loss fraction before turning on the RFKO L_{bf} and the loss fraction in the extraction channel during RFKO extraction process L_{ec} are defined as follows.

$$L_{bf} = \frac{n_{bf}}{n_{bf} + n_{rf}}, \; L_{ec} = \frac{n_{ec}}{n_{rf}}$$

The loss fraction at ES of the circulating beam during the RFKO extraction process L_{ESc}, the loss fraction at the bending magnets of the circulating beam during RFKO extraction process L_{sb} and the loss fraction at MS of the circulating beam during RFKO extraction process L_{ms} are defined as follows.

$$L_{ESc} = \frac{n_{ESc}}{n_{rf}}, \; L_{sb} = \frac{n_{sb}}{n_{rf}}, \; L_{ms} = \frac{n_{ms}}{n_{rf}}$$

The extraction efficiency during RFKO extraction process E_{RFKO} and the total extraction efficiency E_{to} are defined as follows.

$$E_{RFKO} = \frac{n_{ex}}{n_{rf}}, \; E_{to} = \frac{n_{ex}}{n_{bf} + n_{rf}}$$

SIMUALTION AND OPTIMIZATION

The initial 10 MeV beam distribution's horizontal rms emittance is 10 π mm·mrad and rms momentum spread is 1 ‰. The simulated particle number is 1×10^{11}, a little more than the experimental condition (9×10^{10}).

Firstly, a simulation is conducted under a condition similar to the experimental condition. The horizontal tune Q_x and chromaticity Q'_x, vertical tune Q_y and chromaticity Q'_y, normalised resonance sextupole strength *SR*, normalised chromaticity sextupole strength *SC* (for 10 MeV protons, chromaticity sextupole can only provide a maximum normalized strength of 12.5 m^{-3}), stable triangle phase-space area A_{tri}, extraction separatrix angle θ at ES in normalised phase space, ES inner electrode's inclination angle θ_{ES}, spiral step Δx in real phase space are shown in Table 1.

Table 1: Simulation Parameters Similar to the Experimental Condition

	Value		Value
Q_x	1.6627	Q_y	1.6305
Q'_x	-2.31	Q'_y	-1.43
$SR1$	14 m^{-3}	$SR2$	-36 m^{-3}
$SC1$	-12.5 m^{-3}	$SC2$	12.5 m^{-3}
A_{tri}	5.9 π mm·mrad	θ	2.9°
θ_{ES}	0 mrad	Δx	4 mm

In Table 1, Q_x and four sextupoles' normalised strengths are basic parameters which determine the A_{tri}, θ and Δx. θ_{ES} has to be designed to match the beam inclination angle at the ES inner electrode. What's more, a so-called Hardt Condition [2] should be guaranteed by adjusting Q'_x to align the extraction separatrices for all momenta and thus minimises the beam loss at the electrode.

The total number of simulated turns is 35000. To shorten the simulation, the sextupoles' strengths rise to the design value during the first 5000 turns. RFKO is turned on from the 5001st until the 35000th turn. The actual extraction time for 30000 turns is about 21ms. The beam is excited by a dual frequency scanning signal [9], with a center frequency of 4.662 times the revolution frequency, bandwidth of 0.03 times the revolution frequency and a scanning period of 2500 turns.

Simulated beam loss and extraction efficiency are shown in Table 2. And the particles entering ES in the phase space of the ES entrance are shown in Fig. 1.

Table 2: Simulated Results

	Value/ %		Value/ %
L_{bf}	20	L_{ms}	13
L_{ec}	20	L_{sb}	1
L_{ESc}	0		
E_{RFKO}	66	E_{to}	53

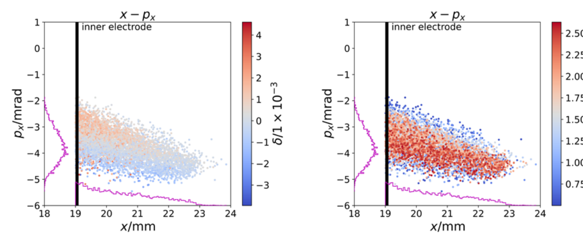

Figure 1: Phase space of the particles at the entrance of ES with different fractional momentum offset δ (left) and extracted turns (right).

From Table 2, the total extraction efficiency is 53%, in agreement with the experimental result which validates the reliability of the simulation result. L_{bf}, L_{ms} and L_{ec} are three main factors reflecting the beam loss.

L_{bf} and L_{ms} can be reduced by optimizing A_{tri}, θ and Δx. The optimized A_{tri}, θ and Δx and corresponding Q_x and four sextupoles' normalised strengths can be obtained just by theoretical analysis and calculation [2] if the space charge effect can be neglected. However, due to the time varying incoherent shift and spread during extraction, the optimal Q_x and four sextupoles' normalised strengths can only be found by simulation. At this point, the theory can roughly provide the direction for parameter optimization: increasing A_{tri} and reducing Δx. θ would be best limited between 0° and 30°.

A large L_{ec} means too many particles lost in the extraction channel, especially in ES. Two factors lead to the loss in ES. One is the 0.1 mm thick inner electrode which is shown in Fig.1 contributing to about 4% loss fraction. The 4% loss fraction will increase when reducing Δx, as mentioned above.

The other is that the θ_{ES} does not match the beam inclination angle at the ES inner electrode, which contributes to about 16% loss fraction. As can be seen from Fig. 1, the average beam inclination angle at 19 mm is about -3.5 mrad while the ES inclination angle θ_{ES} is 0 mrad. Moreover, the extraction separatrices' alignment for all momenta failed with about 2 mrad angle width (-2 ~ -4 mrad) at 19 mm in Fig. 1. Since the Hardt Condition only considers the

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tune spread caused by chromaticity, the additional tune shift and spread caused by the space charge effect will invalidate the Hardt Condition leading to the beam inclination angle width increased. As more and more particles are extracted, the space charge force becomes weaker and weaker. So, the extraction separatrix is constantly varying. This phenomenon will also increase the beam inclination angle width as shown in Figure 1 (right). In short, θ_{ES} can be optimized preliminarily according to the beam inclination angle at the entrance of ES in simulations. But (L_{ec}+L_{Esc}) won't be fully minimized since θ_{ES} is constant during extraction and the Hardt Condition lapses.

Based on the above analysis, a set of optimized parameters is obtained through multiple simulations and comparisons and shown in Table 3.

Table 3: Optimized Simulation Parameters

	Value		Value
Q_x	1.6633	Q_y	1.6316
Q'_x	-0.169	Q'_y	-2.56
$SR1$	6.7 m^{-3}	$SR2$	-5.7 m^{-3}
$SC1$	-12.5 m^{-3}	$SC2$	12.5 m^{-3}
A_{tri}	11.27 π mm·mrad	θ	14.5°
θ_{ES}	-1.25 mrad	Δx	2.5 mm

The other parameters are the same as in the first simulation. The beam loss fraction and extraction efficiency obtained with the optimized parameters are shown in Table 4.

The particles entering ES in the phase space of the ES entrance are shown in Fig. 2.

Table 4: Optimized Simulated Results

	Value/ %		Value/ %
L_{bf}	8	L_{ms}	3
L_{ec}	9	L_{sb}	1
L_{ESc}	5		
E_{RFKO}	82	E_{to}	75

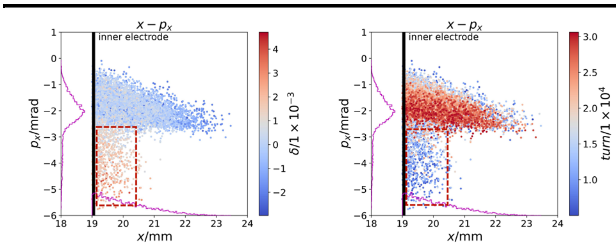

Figure 2: Phase space of the particles at the entrance of ES with different fractional momentum offset δ (left) and extracted turns (right). Particles with larger inclination angles are circled as a rough indication.

In Table 4, with optimized parameters, the total extraction efficiency is promoted to 75%. L_{ESc} becomes larger compared to the first simulation due to the change of θ_{ES} from 0 mrad to -1.25 mrad. L_{bf}, L_{ec} and L_{ms} have been reduced to about 10% with optimized parameters.

Due to the horizontal chromaticity and dispersion, particles with positive momentum spread have bigger A_{tri} and may even exceed the allowed maximum stable region area at ES. Figure 2 (left) shows that the circled particles with positive momentum spread and larger inclination angles enter ES without reaching third order resonance which can be seen from their beam width (20.5 mm-19 mm) of 1 mm smaller than the spiral step Δx (2.5 mm). And almost all the particles with larger inclination angles will be lost at the ES. From the right figure of Figure 2, it shows that these particles with positive fractional momentum offset are extracted first.

Based on the analysis above, it is natural to think to reduce the proportion of particles with positive fractional momentum offset. A possible way is to increase all magnets' strengths with the same ratio before turning on RFKO which is like the Constant Optics Slow Extraction (COSE) [10, 11]. The reference momentum p_{ref} is increased with machine optics unchanged during the process. The difference with COSE is that this operation aims not to extract particles but to vary the average momentum offset (p_{ave}-p_{ref})/p_{ref} of the beam to be negative by increasing the reference momentum p_{ref}.

All magnets' strengths are increased to 1.0005 times the design value during the first 5000 turns. θ_{ES} is changed to -1 mrad and the other parameters are the same as in the simulation with the optimized parameters. Simulation results obtained with the new method are shown in Table 5. The particles entering ES in the phase space of the ES entrance are shown in Fig. 3.

Table 5: Simulated Results with new method

	Value/ %		Value/ %
L_{bf}	9	L_{ms}	3
L_{ec}	6	L_{sb}	1
L_{ESc}	1		
E_{RFKO}	89	E_{to}	81

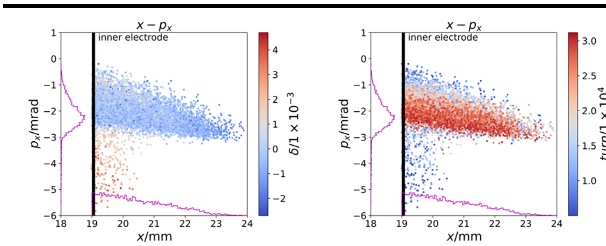

Figure 3: Phase space of the particles at the entrance of ES with different fractional momentum offset δ (left) and extracted turns (right) with the new method.

What's exciting is that the total extraction efficiency is increased by about 6% compared to Table 4. And the amount of particles with larger inclination angles is reduced compared to Fig. 2.

CONCLUSION

Through 10 MeV proton beam extraction simulation and optimization, the total extraction efficiency and the extraction efficiency during RFKO process are improved to 81% and 89% with 1×10^{11} particles stored before extraction.

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The optimized parameters and the new COSE-like method will provide a reference for subsequent experiments.

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