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STUDY ON XiPAF SYNCHROTRON NONLINEAR DYNAMICS*

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Abstract

Xi'an Proton Application Facility (XiPAF) has been operational since 2020, which can accumulate 2×10^{11} protons after injection and 1×10^{11} protons after acceleration. In this paper, we have investigated the XiPAF synchrotron nonlinearity by simulation and experiments. The beam loss occurs with the resonance $\nu_x + 2\nu_y = 5$ in the absence of space charge, and the resonance $2\nu_x - 2\nu_y = 0$ in the presence of space charge. The stripping foil also plays an important role due to its multiple scattering effect and ionization energy loss effect.

INTRODUCTION

The Xi'an Proton Application Facility (XiPAF) is the first facility that is dedicated to simulations of the space radiation environment in China [1], which consists of a 7 MeV linac injector and a compact 200 MeV synchrotron. After several rounds of machine studies and experiments from 2020, the XiPAF synchrotron can accumulate 2×10^{11} protons after injection and 1×10^{11} protons after acceleration [2, 3].

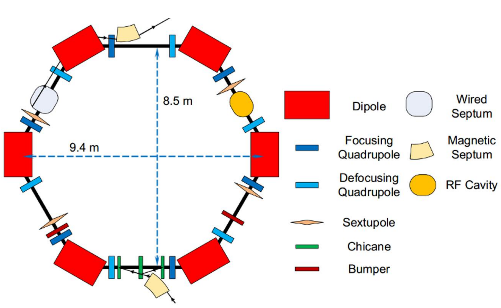

Figure 1: XiPAF synchrotron lattice layout.

The XiPAF synchrotron has 6 periods, with a "missing dipole" lattice structure, shown as Fig. 1. The circumference is 30.9 m, stripping injection turns negative hydrogen beam to proton beam, then the RF cavity voltage ramps from 60 V to 600 V within 10 ms adiabatically, and accelerates particles to 200 MeV. The main parameters are shown in Table 1, and the lattice beta functions are shown as Fig. 2.

During beam commissioning, we found that nonlinear resonance is the main limitation during injection, capture and acceleration. In this paper, the nonlinear dynamics of the XiPAF synchrotron have been studied, with and without space charge. Possible resonance has been analysed in tune diagram, resonance stopband scan has been used to identify the nonlinearity of the XiPAF synchrotron by simulation and experiment, and the space charge effect has also been discussed.

Table 1: XiPAF Synchrotron Main Parameters

Parameters	Values	Units
Periodicity	6	
Circumference	30.9	m
Injection Energy	7	MeV
Injection Tune ν_x/ν_y	1.74 / 1.70	
Extraction Energy	10~200	MeV
Extraction Tune ν_x/ν_y	1.68 / 1.72	
Natural Chromaticity	−0.32 / −2.39	
Momentum Compaction	0.34	

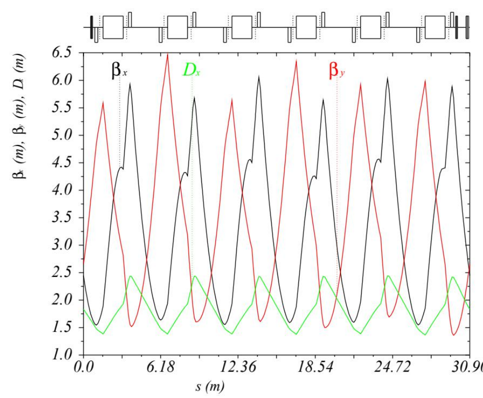

Figure 2: XiPAF synchrotron lattice optics.

RESONANCE LINE AND HAMONIC ANALYSIS

The XiPAF synchrotron has 6 periods. Lattice optics functions are shown as Fig. 2, beta function is not fully symmetric according to the 3 chicane magnets located in the injection long drift section, which are used for stripping injection. Harmonic analysis of beta function shows that the strongest harmonic number is 6 (as shown in Fig. 3), which is the same with the lattice period. Because of the symmetry distortion of chicane magnets, the strength of all harmonic

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numbers is non-zero, this means that the resonance could be induced by any harmonic number.

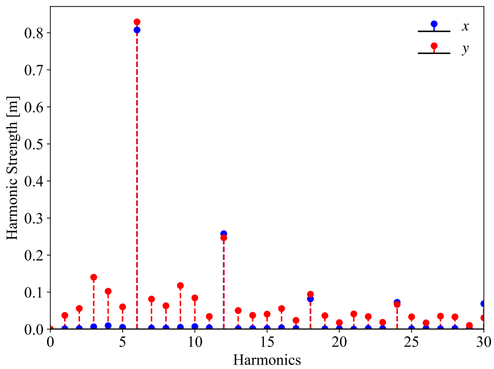


Figure 3: XiPAF synchrotron beta function harmonic analysis.

Based on the lattice harmonic analysis results, we can understand that those resonances with the harmonic number of multiples of 6 are the most dangerous, which are the structure resonances. Resonance lines near the injection and extraction tune are shown in Fig. 4, red lines are structure resonance and blue lines are non-structure resonance but excited by normal high order fields. Critical structure resonance may be $\nu_x - \nu_y = 0$, and non-structure resonance may be $\nu_x + 2\nu_y = 5, 3\nu_x = 5$ in our interested tune region.

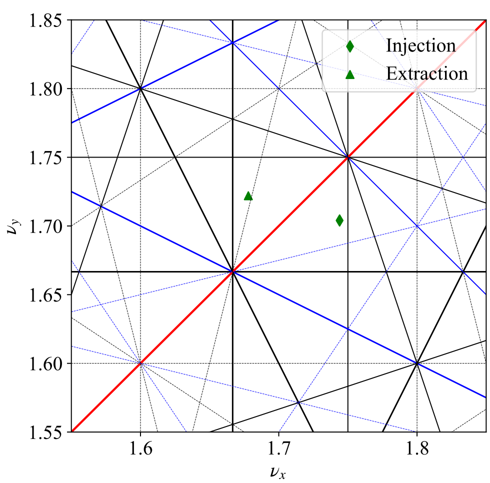


Figure 4: XiPAF synchrotron tune diagram.

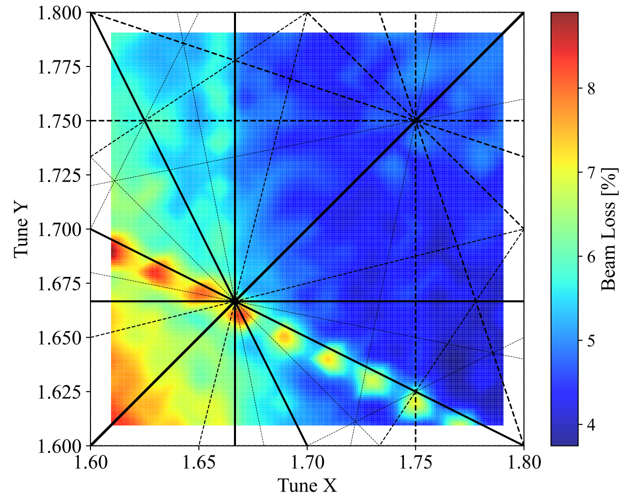
RESONANCE STOPBAND SCAN

Static resonance stopband scan has been used to study the nonlinear beam loss and space charge effect [4].

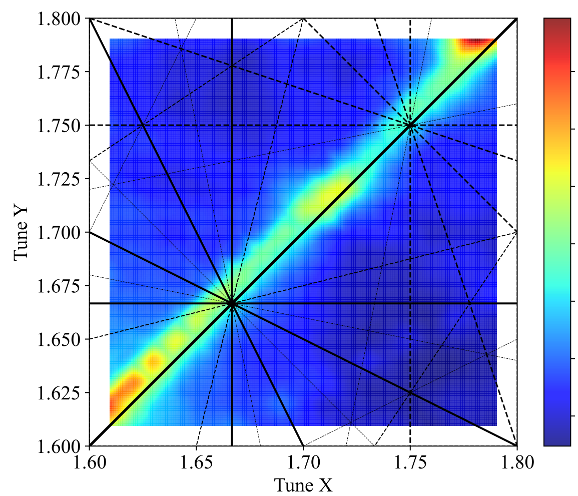
Simulation

The simulation has been performed using the PyORBIT Code. In the simulation, we added no field errors or alignment errors, the nonlinearity only comes from PyORBIT tracking algorithm.

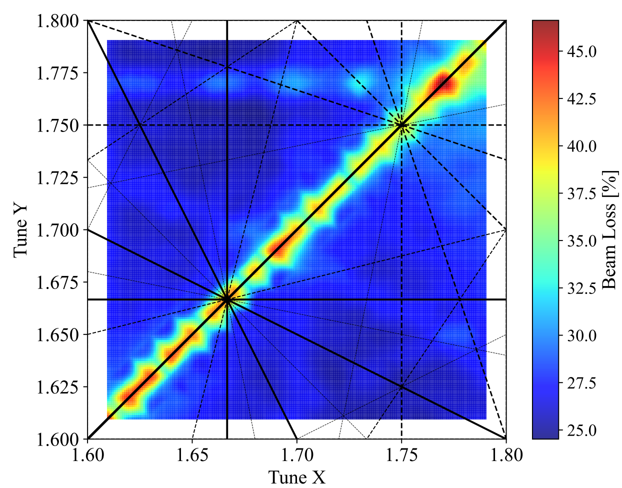
First, we perform the simulation for coast beam. After injection, 2×10^{11} particles are stored in the synchrotron,



(a) Coast beam, without space charge, foil thickness 5 µg/cm^2



(b) Coast beam, with space charge, foil thickness 5 µg/cm^2



(c) Coast beam, with space charge, foil thickness 20 µg/cm^2

Figure 5: Beam loss for coast beam.

nonlinear resonance and space charge increase the beam emittance and cause beam loss. Without space charge, the main beam loss is caused by the resonance line $\nu_x + 2\nu_y = 5$, with the maximum beam loss of about 9%, as shown in Fig. 5.

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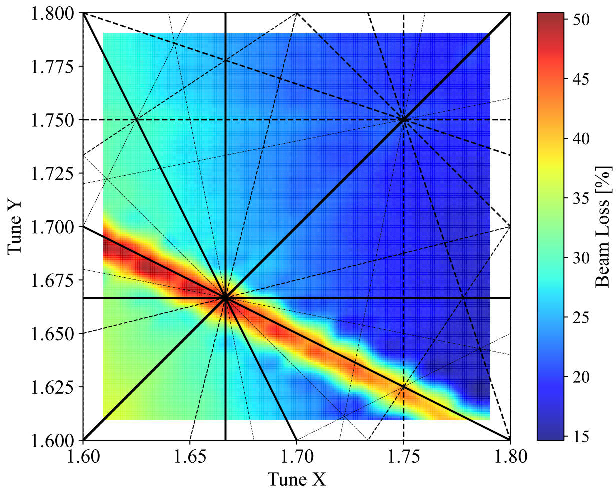
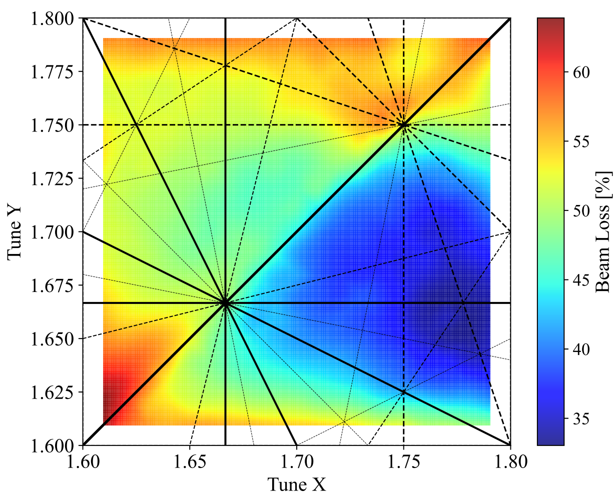
For the space charge case, the main resonance line changes to $2\nu_x - 2\nu_y = 0$, and the maximum beam loss is about 19%, as shown in Fig. 6. If we choose the foil thickness as 20 μg/cm^2, the maximum beam loss is about 46%, which means the multiple scattering effect and ionization energy loss effect have a great influence on beam loss.



(a) Bunch beam, without space charge, foil thickness 5 μg/cm^2



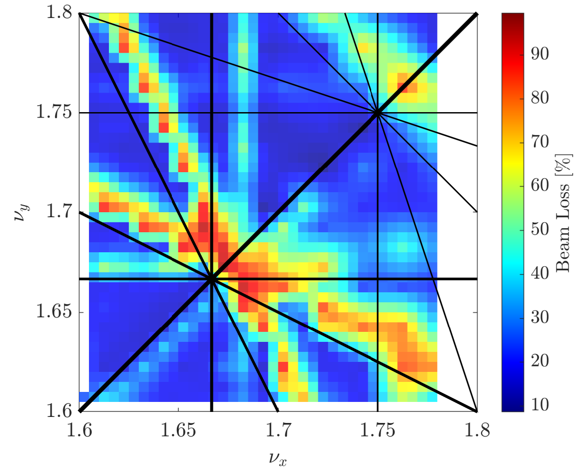
(b) Bunch Beam, without space charge, foil thickness 5 μg/cm^2

Figure 6: Beam loss for bunch beam.

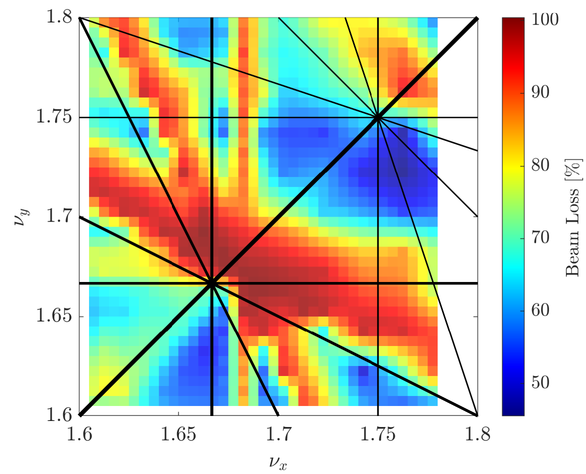
For a bunch beam, without space charge, we get a similar beam loss pattern as for coast beam, but the pattern is quite different for space charge case, the main resonance line is still $2\nu_x - 2\nu_y = 0$, and the space charge tune shift makes beam easier to lose above the resonance line, which makes the beam loss at the different sides of the resonance line $2\nu_x - 2\nu_y = 0$ different.

Measurement

Figure 7 shows the measured beam loss on XiPAF synchrotron, we can see a similar beam loss at the resonance line $\nu_x + 2\nu_y = 5$, as well as other resonances such as $2\nu_x + \nu_y = 5$, $3\nu_x = 5$, $3\nu_y = 5$ and $2\nu_x + 2\nu_y = 7$, which may be due to alignment errors and field errors. The beam



(a) Coast Beam



(b) Bunch Beam

Figure 7: Measured beam loss for coast beam and bunch beam.

loss at $2\nu_x - 2\nu_y = 0$ is not so serious, that because the particle number in synchrotron is about 6.4×10^{10} when the measurement was taken, the space charge effect is not so strong.

Additionally, we can see that the synchrotron motion in the bunch beam case enlarges the stopband width, the beam loss is more serious, as we expected.

CONCLUSION

The nonlinear dynamics of the XiPAF synchrotron have been studied through analysis, simulation and experiment. The main resonance is $\nu_x + 2\nu_y = 5$ for the no space charge case and $2\nu_x - 2\nu_y = 0$ for the space charge case. The stripping foil plays an important role in beam loss by increasing the emittance. The synchrotron motion enlarges the stopband width, making the beam loss more serious.

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