ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPM136

LATTICE CONSIDERATIONS FOR SYNCHROTRON OF XiPAF-UPGRADING PROJECT*

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Abstract

The synchrotron of XiPAF (Xi'an 200 MeV proton application Facility) is a compact proton synchrotron, which can accumulate and accelerate 1×10^{11} particles for 3-order resonance slow extraction, with H^- stripping injection and phase space painting scheme. Now XiPAF is under the challenge of more particle species for single event effect study, like He^+, C^{4+} and so on. This paper reports the lattice considerations and beam dynamic study for XiPAF-Upgrading synchrotron, shows that XiPAF synchrotron upgrade is feasible by using original dipoles, quadrupoles and sextupoles.

INTRODUCTION

The Xi'an 200 MeV Proton Application Facility (XiPAF) is a proton facility, providing proton beam up to 230 MeV for the study and evaluation of single event effect on core electronics for astronautics [1], located in Xi'an, China. The main part of the XiPAF machine is a synchrotron with a circumference of 30.9 m and six-ford symmetry. 7 MeV negative hydrogen is injected into the synchrotron as coasting beam and stripped to proton by foil, then it reaches various energies ranging from 10 to 200 MeV for 3-order resonance slow extraction, after phase space painting, RF capture and acceleration.

After beam commissioning in 2020, XiPAF synchrotron can accumulate 2×10^{11} protons after injection [2] and 1×10^{11} protons after acceleration [3]. The working point is (1.74,1.70) for injection and (1.68, 1.72) for extraction. The facility has been operational since 2020 and has experiments for different users.

However, with the increasing demand for space radiation experiments, a wider range of ions is needed, rather than just protons. XiPAF needs to upgrade its current proton synchrotron to a multi-ion synchrotron, which can accelerate not only proton but also several heavy ions. Heavy ions are He^+, C^{4+}, Si^{8+}, Ar^{11+}, Kr^{18+}, Bi^{32+}.

One of the main technical challenges is to redesign the synchrotron with original magnets and lattice structure for cost and lead time saving. Injection and extraction energies of different ions are based on maximum magnet field, listed in Table 1. In this paper, a lattice for a proton and heavy ion synchrotron reusing the original magnets is reported.

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Table 1: XiPAF-Upgrading Synchrotron Injection and Extraction Energies

Ion	Injection Energy [MeV/u]	Maximum Extraction Energy [MeV/u]
proton	7	200
He^+	2	4
C^{4+}	2	9
Si^{8+}	2	7
Ar^{11+}	2	4
Kr^{18+}	2	6
Bi^{32+}	2	6

LATTICE CONSIDERATIONS

Lattice Optics

In order to carry out the injection of multiple ions, such as He^+ or C^{4+} besides protons, XiPAF's original stripping injection system could not meet the requirements and multi-turn injection scheme must be used. As a result, the original Chicane magnets and stripping foil equipment needed to be removed from the synchrotron, and injection magnetic septum and injection electrostatic septum were used as injection equipment, while, in order to control and adjust the height and angle of the injection bump orbit more accurately at the injection point, two more injection bump magnets are required, so the installation space required for the injection system increased significantly. XiPAF's original long drift section did not have sufficient installation space and had to be lengthened.

XiPAF-Upgrading synchrotron extraction system follows the original resonance slow extraction scheme, i.e. a extraction electrostatic septum and a magnetic septum are used to extract beam out of the synchrotron, and beam are deliverd by RTBT to the target station.

The lattice redesign is based on original dipoles, quadrupoles and new drift sections. XiPAF-Upgrading synchrotron has the same symmetry and structure with original proton synchrotron, but larger circumference, as shown in Figure 1, synchrotron circumference increase to 39.96 m from 30.9 m.

Increasing circumference reduce the strength of defocusing quadurpoles, if we choose the same working point with original synchrotron. Due to XiPAF dipole edge focusing, defocusing quadrupole strength will be close to zero, even

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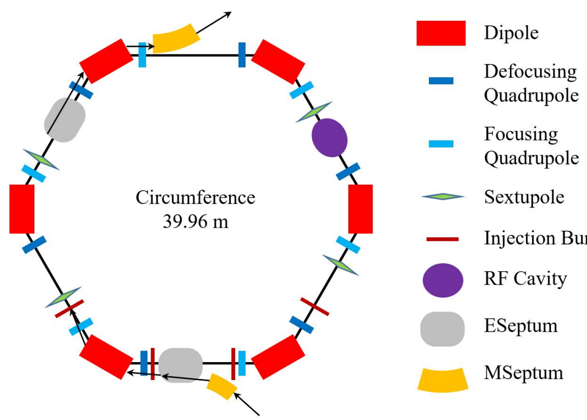

Figure 1: XiPAF-Upgrading synchrotron lattice layout.

turn defocusing quadrupole to focusing quadrupole, if we keep working point unchanged. This means that ripple in quadrupole power supplies will significantly affect machine tune, make beam unstable and hard to control when extraction near 3-order resonance. So ν_y is set to 2.26, which is above $\nu_y = 2$, beam dynamics is different from original $\nu_y = 1.70$. New lattice optics is shown in Figure 2, tune adjustment range is shown in Figure 3. Main parameters are listed in Table 2.

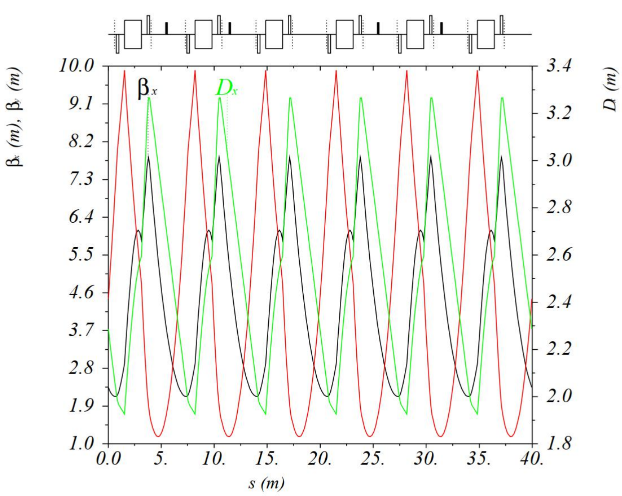

Figure 2: XiPAF-Upgrading synchrotron lattice optics.

Table 2: XiPAF-Upgrading Synchrotron Parameters

Parameters	**Injection**	**Extraction**
Periodicity	6	6
Tune ν_x/ν_y	1.73/2.26	1.68/2.26
Natural Chromaticity	-0.08/-3.50	-0.03/-3.39
Max. β_x [m]	7.65	7.53
Max. β_y [m]	9.90	9.75
Max. D_x [m]	3.27	3.40
Momentum Compaction	0.37	0.39

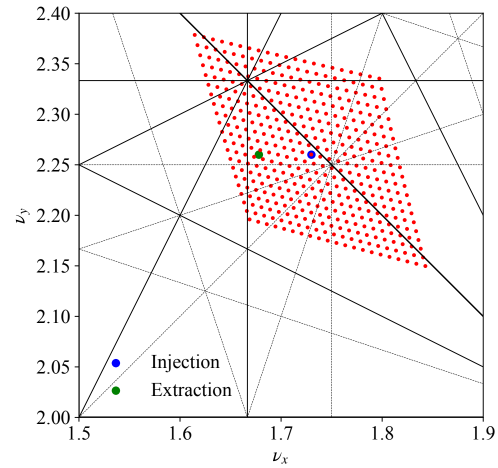

Figure 3: XiPAF-Upgrading synchrotron lattice tune change range.

For proton, injection working point is set to (1.73, 2.11). If tune is set to (1.73, 2.26), space charge and lattice nonlinearity can induce nonlinear couple resonance $\nu_x + 2\nu_y = 6$, horizontal and vertical beam emittance grow up, then particles reach vertical vacuum pipe, causing massive beam lost during RF capture and acceleration.

For heavy ions, injection working points are still set to (1.73, 2.26), this working point can avoid multiple resonance crossing during acceleration, when tune changes from injection working point to extraction working point.

BEAM DYNAMICS

In this section, closed orbit distortion, correction and dynamic aperture are reported.

Orbit Correction

Alignment errors are unavoidable, and closed orbit distortion appears. Six type alignment errors are considered, Δx, Δy, Δs, $\Delta\phi$, $\Delta\theta$, $\Delta\psi$, which is the same with MADX.

Closed orbit distortion under 1000 sets of random alignment errors are calculated. The random alignment error distribution is assumed as uniform. According to the XiPAF alignment error level, position alignment errors amplitude are set to 0.2 mm and the angle alignment errors are set to 0.3 mrad. The maximum and rms closed orbit distortion as shown in Figure 4, orbit distortion in y dimension is much sensitive, maximum orbit distortion is about 7 mm, comparing with 2 mm in x dimension. Closed orbit distortions for injection lattice and extraction lattice are similar and the maximum orbit distortion is the same for both lattice. Dipole's Δy, $\Delta\psi$ error and quadrupole's Δx, Δy error have the greatest influence on closed orbit distoritions, which should be strictly controlled.

XiPAF-Upgrading synchrotron has 6 correctors in both dimension. After correction, maximum closed orbit distortion is less than 1 mm, and required corrector strength are

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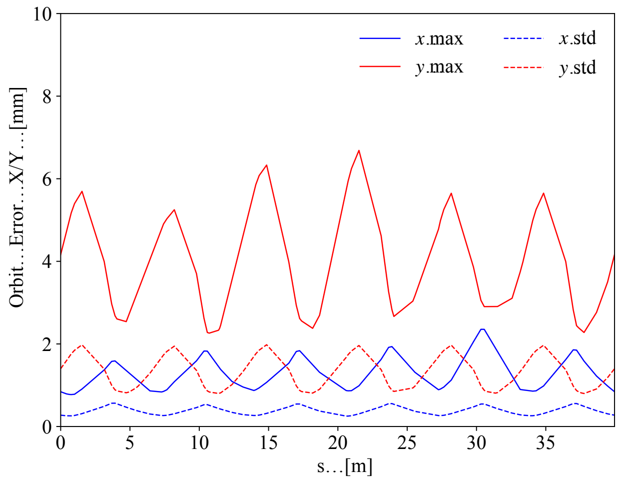

Figure 4: Closed orbit errors before correction.

shown in Figure 5, maximum kick angle is less than 1 mrad.

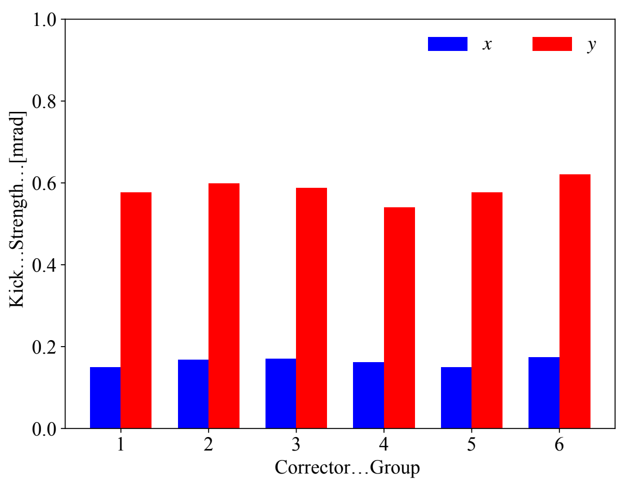

Figure 5: Corrector strength required by closed orbit correction.

Dynamic Aperture

Magnet field errors must be considered. Due to the reuse of dipoles and quadrupoles, all magnets' field errors have been measured, these measured high order nonlinear field errors are used to evaluate dynamic aperture, as shown in Fig. 6, high order field errors in dipoles is the main limit to XiPAF-Upgrading synchrotron dynamic aperture because of its large effective length.

Besides high order field, due to the serial connection of dipole magnets, different dipole magnets' dipole field may be not exactly the same, even with the same magnet current, so as quadrupoles. These non-uniformity field errors' effect on closed orbit and tune are also evaluated. 0.01% field errors in dipoles may cause 1.31 mm closed orbit distorition in x dimension and no closed orbit distorition in y dimension. Their effect on tune is shown in Table 3, under 0.01% field

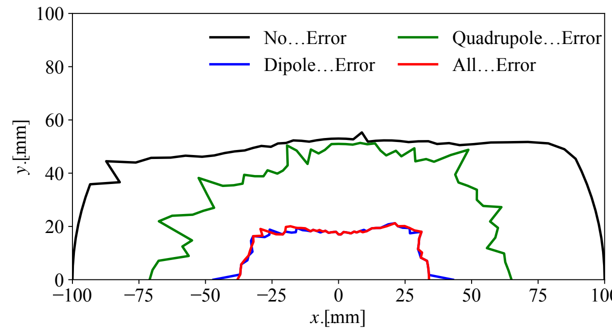

Figure 6: Dynamic aperture at injection electrostatic deflector exit.

error level. Main effect is caused by dipoles' quadrupole field, which can be corrected by synchrotron quadrupoles.

Table 3: Effect of Field Errors on Tune

Error Type	$\Delta\nu_x$	$\Delta\nu_y$
Dipole $\Delta B/B$	0.00001	0.00002
Quadrupole $\Delta K/K$	0.00013	0.00012
Dipole's Quadrupole Field	0.00413	0.00417

CONCLUSION

This paper introduces the synchrotron lattice considerations of XiPAF-Upgrading project, circumference has increased to 39.96 m for multiturn injection equipments and machine tune are adjusted to (1.73, 2.11) for proton and (1.73, 2.26) for heavy ions, space charge effect has been optimized and field errors have been studied. Lattice optics and beam dynamics show that XiPAF synchrotron upgrade is feasible by using original dipoles, quadrupoles and sextupoles.

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