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THE DESIGN OF A PROTON-HEAVY ION HYBRID SYNCHROTRON UPGRADED FROM XIPAF PROTON RING

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Abstract

Xi'an 200 MeV Proton Application Facility (XiPAF) has been basically completed at the end of 2020, providing proton beams of 10 to 200 MeV for space radiation effect studies on electronics. To expand its capabilities, XiPAF is undergoing an upgrade to deliver multiple ion species, from proton to Bismuth ion. The upgrade focuses on three aspects. First, the original negative hydrogen linear injector will be remodelled to a proton linac injector. Second, a heavy ion linear injector will be added. Third, the existing proton ring will be retrofitted into a hybrid proton-heavy ion synchrotron. This paper details the considerations and physical designs for upgrading the synchrotron. Within the scope, we discuss the challenges and solutions in transforming a specialized proton synchrotron into a multi-ion accelerator under the constraints of existing plant layout and reuse of existing equipment.

INTRODUCTION

XiPAF is a dedicated facility for space radiation environment simulation. It has been designed since 2014, and the beam commissioning was completed in a temporary plant at the end of 2020 [1], providing 10 ~ 200 MeV proton beams for irradiation experiments, while the formal plant is also under construction. With the continuous development of space radiation effect studies, new demands have been put forward for the device. Therefore, the XiPAF-Upgrading project was proposed and approved. The requirements and basic principles of XiPAF-Upgrading are:

- Expanding ion species from protons to multiple ions containing protons and heavy ions.
- The size of the upgraded accelerator complex is required to be within the layout of the plant under construction.
- Reuse the original equipment of XiPAF as much as possible to reduce costs.

XiPAF-Upgrading project began design in 2022 and beam commissioning is scheduled to be completed by the end of 2025. The overall layout of XiPAF-Upgrading is shown in Fig. 1. The original H^- linac injector of XiPAF will be changed to H^+ injector with an energy of 7 MeV. A set of heavy-ion linac injector will be added, the charge-to-mass ratio range of the heavy ions to be accelerated is 1/2~1/6.5, and the energy is 2 MeV/u. The original proton ring will be upgraded to a proton-heavy ion hybrid synchrotron, and two terminals are for proton and heavy ion experiments respectively.

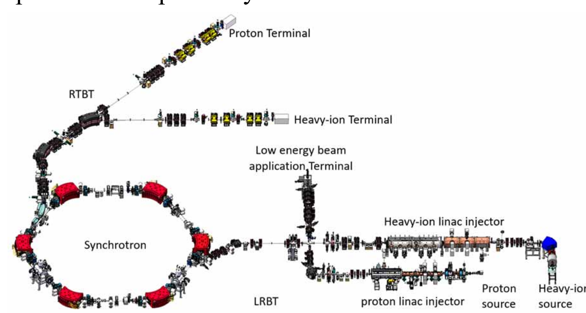

Figure 1: The overall layout of XiPAF-Upgrading.

The main parameter requirements of XiPAF-Upgrading synchrotron are shown in Table 1. The existing equipment needs to be reused, and the size of the synchrotron is limited by the size of the plant (ring circumference ≤ 40 m). Under these constraints, the physical design of the proton-heavy ion hybrid synchrotron upgraded from a proton ring is reported.

Table 1: Design Requirements of XiPAF-Upgrading Synchrotron

Ion	Injection Energy [MeV/u]	Extraction Energy [MeV/u]	Particle No. [ppp]
H^+	7	10~200	1×10^{10}
He^+	2	4	1×10^{8}
C^{4+}	2	9	1×10^{8}
Si^{8+}	2	7	1×10^{7}
Ar^{11+}	2	4	1×10^{7}
Kr^{18+}	2	6	1×10^{7}
Bi^{32+}	2	6	1×10^{7}

LATTICE DESIGN

To upgrade XiPAF proton ring to a proton-heavy ion hybrid synchrotron, two major issues need to be addressed: (1) vacuum; (2) injection. To meet the requirements of the heavy-ion beam lifetime, the vacuum pressure of the synchrotron needs to be upgraded from 1×10^{-6} Pa to 5×10^{-10} Pa. XiPAF proton ring adopts the H^- stripping injection, to

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inject multi-ions, the multiturn injection scheme needs to be adopted. Therefore, the vacuum system and injection system need to be greatly modified. More equipment installation space is required, that is, the circumference of synchrotron needs to be increased. To reuse the existing dipoles and quadrupoles, the lattice still maintains the original structure of 6 DBFO cells [2], and six straight sections are lengthened. The circumference of the synchrotron is increased from 30.9 m to 39.96 m.

The horizontal tune remains unchanged; if the vertical tune is maintained as the circumference of the synchrotron increases, the strength of the defocusing quadrupoles will decrease to close to zero. Under low current operation, the power supply ripple of the defocusing quadrupole will significantly affect the machine working point, causing beam instability. Therefore, it is necessary to increase the vertical tune to above 2. The injection tune for heavy ions is selected as (1.73, 2.26). For protons with high intensity, at (1.73, 2.26), the space charge effect and lattice nonlinearity will induce coupled resonance $\nu_x + 2\nu_y = 6$, resulting in beam loss. Therefore, the injection tune for protons is adjusted to (1.73, 2.11). After the lattice parameters were determined, the influence of the magnetic field errors on closed orbit and dynamic aperture was studied and the detailed results can be found in the Ref. [3].

INJECTION SYSTEM

To achieve full ions injection, the original negative hydrogen stripping injection scheme needs to be changed to a multiturn injection scheme. The injection system transformation includes:

- Remove the stripping foil equipment and Chicane magnets in the original injection section and add an injection electrostatic septum (ESi).
- Increase the number of bumper magnets (BP1~BP4) from the original two to four to independently adjust the position and angle of the orbit bump at the injection point.
- Redesign an injection magnetic septum (MSi) to meet new injection requirements.

The layout diagram of the injection system is shown in Fig. 2.

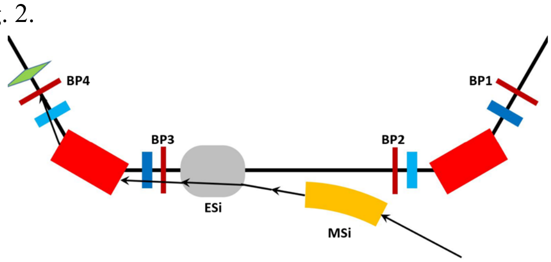

Figure 2: The layout of the injection system.

The main goal of heavy ion injection design is to achieve higher injection efficiency through optimizing the orbit bump curve and the phase space filling, to reduce the influence of beam loss on vacuum. According to the requirements of extraction design, the maximum emittance of each ion after acceleration to the required energy is 100π mm·mrad, calculate the allowable emittance after injection and divide it into three categories for injection optimization: the emittance after injection is 200π mm·mrad (C^{4+}), 170π mm·mrad (Si^{8+}, Kr^{18+}, Bi^{32+}) and 120π mm·mrad (He^{+}, Ar^{11+}) respectively. The multiturn injection simulation was performed using PyORBIT. After the bump curve optimization, the injection efficiencies of heavy ions have been improved to above 75%, as shown in Table 2.

Table 2: Simulation Results of Multiturn Injection

Ion	Injection Intensity [eμA]	Injection Efficiency	Particle No. [ppp]
H^{+}	2000	87%	7.2×10^{10}
He^{+}	35	78%	3.1×10^{9}
C^{4+}	69	86%	2.3×10^{9}
Si^{8+}	25	76%	3.4×10^{8}
Ar^{11+}	32	75%	2.5×10^{8}
Kr^{18+}	40	75%	2.6×10^{8}
Bi^{32+}	20	78%	7.5×10^{7}

Limited by Liouville's theorem, the injection gain of XiPAF-Upgrading synchrotron using multiturn injection is lower than that of the XiPAF using stripping injection. By increasing the proton beam intensity before injection, the particle number after injection can reach the same level as XiPAF. For example, the beam intensity before injection is 8 mA, and the number of particles after injection is 2.5×10^{11}, but the beam loss is serious during the subsequent capture and acceleration process, and the total efficiency is only 5%.

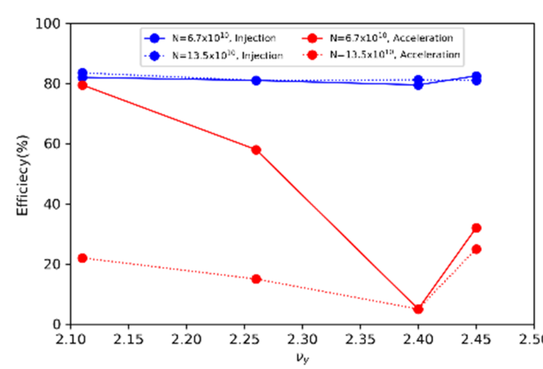

Figure 3: Proton injection and acceleration efficiency varies with vertical tune.

The above problem was studied, and it is found that the main source of beam loss is the transverse coupled resonance $\nu_x + 2\nu_y = 6$. Scan the vertical tune and calculate the injection efficiency and acceleration efficiency as shown in Fig. 3. The injection efficiency is almost same under different tune and different stored particle numbers, but the acceleration efficiency is obviously different. When ν_y is 2.26, the resonance crossing will occur induced by space charge. The vertical emittance increases sharply, resulting in serious beam loss in vertical direction. To obtain higher acceleration efficiency, the working point is selected as (1.73, 2.11) and the number of particles after injection should not be too high, as shown in Table 2.

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CAPTURE AND ACCELERATION

For XiPAF-Upgrading synchrotron, the capture and acceleration parameters of the proton remain the original XiPAF design. In the case of reusing existing equipment as much as possible, it is necessary to design the parameters of heavy ions. The revolution frequency of heavy ions is 0.49 ~ 1.04 MHz, and the operating frequency range of the existing RF system is 1 ~ 6 MHz. To reuse the existing equipment, the harmonic number is selected to be 2 for heavy ion capture and acceleration.

Table 3: Acceleration Parameters and Results of XiPAF-Upgrading Synchrotron

Ion	RF Voltage [V]	Max. Phase [º]	Efficiency [%]
H^+	600	8	47.2
He^+	700	6	99.9
C^{4+}	550	12	87.9
Si^{8+}	650	12	95.9
Ar^{11+}	650	6	99.6
Kr^{18+}	850	10	96.3
Bi^{32+}	1150	10	96.1

The gap voltage and synchronous phase need to be optimized to form a suitable bucket height and area to reduce beam loss during adiabatic capture and acceleration. The design parameters of capture and acceleration and the simulation results for the total efficiency of capture and acceleration are shown in Table 3. Due to the influence of space charge effect, the efficiency of protons is low, and beam loss mainly occurs in the early stage of acceleration. The existing magnetic alloy cavity can be reused, but the power amplifier needs to be upgraded to increase the gap voltage from the original 800 V to above 1200 V.

EXTRACTION SYSTEM

XiPAF-Upgrading synchrotron still adopts the third-order resonance and transverse radio frequency knockout (RF-KO) method to achieve slow extraction. The layout of the extraction elements is like that of the XiPAF synchrotron [4]. It is necessary to find the optimal value under the existing equipment aperture limitation. Comprehensively consider the beam loss in the last three turns before extraction and the number of particles stored in the ring to determine that the maximum emittance before extraction is 100π mm·mrad. The extraction parameters for heavy ions are shown in Table 4.

The trajectories with different momentum dispersions in the last three turns are shown in Fig. 4, the trajectories of particle with the negative momentum dispersion obviously exceed the existing aperture limitation at two chromatic sextupoles (SC02, SC04), resulting in serious beam loss. To improve the extraction efficiency, the existing two chromatic sextupoles cannot be reused, and need to be redesigned to increase the aperture.

The extraction energy range of protons is 10 ~ 200 MeV, so the extraction parameter design is divided into two cases: low energy (10 ~ 60 MeV) and high energy (60 ~ 200 MeV). In the case of high energy extraction, the design parameters can be like those of heavy ions and will not be discussed. Under the condition of low energy and high intensity, the influence of space charge force is great. If the same horizontal tune as the heavy ion is adopted, many particles will be extracted during the turning on of resonant sextupoles. Therefore, for low energy slow extraction, a design scheme of setting the horizontal tune below the third-order resonance line is proposed. Take 10 MeV as an example, the extraction parameters are listed in Table 4.

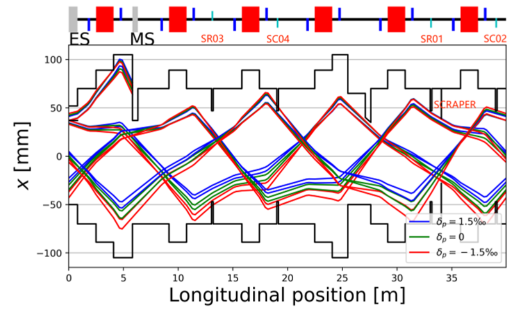

Figure 4: The trajectories in last three turns with different momentum dispersions.

Table 4: Extraction Parameters of XiPAF-Upgrading Synchrotron

Parameters	Heavy ion	Proton (200 MeV)	Proton (10 MeV)
Tune ν_x / ν_y	1.678/2.26	1.678/2.11	1.661/2.11
Corrected Chromaticity	-0.3/-3.3	-1.34/-1.1	-1.2/-1.2
Triangle Area[πμm]	113	108	63

The beam simulation during the extraction phase was carried out using SynTrack, an upgraded version of LiTrack [5]. The space charge effects are considered for proton. The simulation results show that the extraction efficiency of heavy ions and high energy protons is higher than 90%, and the efficiency of 10 MeV protons is 75%. Combined with the results of Table 2 and Table 3, the number of particles extracted from the synchrotron meets the requirements of Table 1 and has sufficient margin.

CONCLUSION

Under the condition of limiting the ring circumference and reusing the existing equipment as much as possible, the physical design of XiPAF-Upgrading synchrotron has been completed. The extraction energy for the proton is 10 ~ 200 MeV, and 4 ~ 9 MeV/u for the heavy ions. The number of particles meets the design requirements. The design of ultra-high vacuum system of XiPAF-Upgrading synchrotron with a vacuum pressure of 5×10^{-10} Pa is a challenge and has been completed and will be reported soon elsewhere.

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