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EXPERIMENT AND SIMULATION STUDY ON THE CAPTURE AND ACCELERATION PROCESS OF XiPAF SYNCHROTRON*

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Abstract

The beam commissioning of capture and acceleration process on the XiPAF (Xi'an 200 MeV Proton Application Facility) synchrotron has been carried out. Efficiency of the experiment results has been compared with the simulation results. At present, the efficiency of capture process with single-harmonic is about 73%, and the acceleration efficiency is about 82%, and the simulation results are 77% and 96% without space charge effect, respectively. In order to improve efficiency, dual-harmonic was used during capture and acceleration process. During the experiment, the capture efficiency was increased by 5%, and the acceleration efficiency was increased by 4%. The capture efficiency decreases with the increase of the maximum RF voltages. We analyzed the reasons for the decreasing of the capture efficiency. In the next step, further verification will be carried out through experiments under different conditions.

INTRODUCTION

Xi'an 200 MeV Proton Application Facility (XiPAF) can be used to simulate the irradiation environment of outer space on the ground, so as to study the space irradiation effect, especially the single particle effect can be further studied. The main body of the whole facility is a synchrotron ring with a circumference of 30.9 m. After the negative hydrogen beam is generated from the ion source, transmitted through the linear injector, and then injected into the synchrotron after stripping electrons, the proton energy at the time of injection is 7 MeV. After the capture and acceleration process of the synchrotron, the proton energy can reach 60-200 MeV at the time of extraction [1]. The radio frequency system of the synchrotron consists of digital low level radio frequency (LLRF) system, solid state power source and magnetic alloy cavity. The frequency bandwidth of the synchrotron is 1 MHz ~ 6 MHz, and the maximum cavity voltage can be generated in the magnetic alloy cavity is 800 V. In order to improve the capture efficiency and acceleration efficiency as much as possible, it is necessary to design and adjust the radio frequency parameters, including optimizing the cavity voltage curves in the capture process and adopting dual-harmonic during acceleration process. At present, the efficiency of capture process with single-harmonic is about 73%, and the acceleration efficiency is about 82%, and the simulation results are 77% and 96% without space charge effect, respectively. In order to improve efficiency, dual-harmonic was used during capture and acceleration process. During the experiment, the capture efficiency was increased by 5%, and the acceleration efficiency was increased by 4%. The capture efficiency of simulation and experiment under different maximum cavity voltages is also compared and analyzed.

ADIABATIC CAPTURE

The injected beam of the XiPAF synchrotron ring comes from the drift-tube linear accelerator, and its operating frequency is 325 MHz, while the cyclotron frequency of the beam in the synchrotron is 1 MHz to 6 MHz. It can be considered that the particles are evenly distributed along the synchrotron ring after the injection. After the injection, beam on the longitudinal phase space occupies a rectangular area, which doesn't match with the "fish" bucket. As shown in Fig. 1, the area surrounded by the black line is the bucket area. Accelerating immediately leads to loss of particles, due to a large amount of particles staying outside of the bucket area. Therefore, the adiabatic capture technology is used to gradually capture the protons into the bucket by slowly increasing the cavity voltage to achieve the purpose of bunching. In the process of adiabatic capture, the lower initial voltage reduces the space charge effect in the beam and inhibits the growth of the beam emittance. In order to improve the longitudinal capture probability, the higher harmonic can be introduced for double harmonic acceleration, which elongates the bunch and weakens the effect of space charge.

In the process of adiabatic capture, the acceleration voltage rises from a small value to the maximum value, which can make the particles gradually enter the bucket in the process of phase motion. The process is reversible.

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Taking the initial voltage as 1/10 of the maximum voltage, the formula of voltage curve is shown in Eq. (1) [2]:

$$V_{pp}(t) = \left[3(\frac{t}{T_v})^2 - 2(\frac{t}{T_v})^3\right](V_1 - V_0) + V_0\,, \qquad (1)$$

where V_0 and V_1 are the initial and final voltage in the adiabatic capture stage, and T_V is the adiabatic capture time.

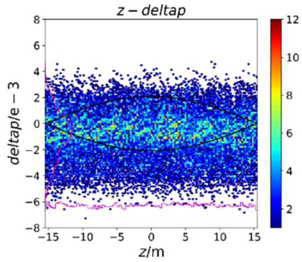

Figure 1: Longitudinal phase space after injection.

After adiabatic capture, the distribution of beam will change from a uniform distribution to a distribution that fits the bucket shape, as shown in Fig. 2. The particles distributed at the edge of the bucket are the particles that may be lost after capture.

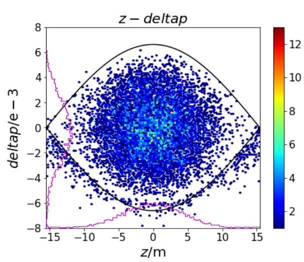

Figure 2: Longitudinal phase space after capture.

Through the reverse operation of the radio frequency cavity voltage, the beam can be debunched in the longitudinal phase space. Figure 3 shows the beam distribution in the longitudinal phase space before and after the cavity voltage is reduced from 600 V to 40 V, after the particles are bunched by a voltage of 0 to 600 V and the beam is accelerated to 10 MeV by 600 V. It can be seen that the bunched beam is successfully debunched through a reverse operation of capture, which is also a classic method to manipulate the longitudinal phase space of the beam.

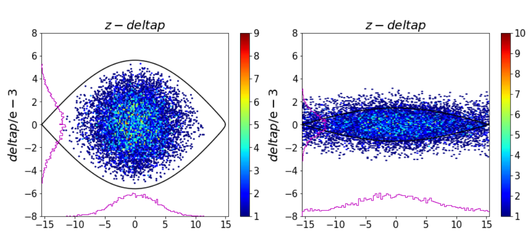

Figure 3: Longitudinal phase space before (left) and after (right) debunching process.

DUAL-HARMONIC ACCELERATION

In order to weaken the space charge effect, the second harmonic can be used to elongate the beam bunch. The phase motion equation under dual harmonic can be derived from the following Hamiltonian [3]:

$$H = \frac{1}{2}\frac{h\eta\omega_0^2}{\beta^2 E}(\frac{\Delta E}{\omega_0})^2 + \frac{e}{2\pi}V(\phi)\,, \qquad (2)$$

where

$$V(\phi) = V_1\left[\cos\phi - \cos\phi_{1s} + (\phi - \phi_{1s})\sin\phi_{1s}\right] +$$
$$V_2\left[\frac{h_1}{h_2}\cos(\phi_{2s} + \frac{h_2}{h_1}(\phi - \phi_{1s})) - \cos\phi_{2s} + (\phi - \phi_{1s})\sin\phi_{2s}\right].$$

Subscript "1" and "2" denote fundamental and second harmonic radio frequency wave parameters respectively. The longitudinal motion of particles can be compared to a ball oscillating back and forth in a potential well *V(ϕ)*.

To lengthen the beam bunch, we need to make the *V(ϕ)* slightly flattened. During the adiabatic capture process, the synchronous phases both are zero. *r* is defined as harmonic voltage ratio: $r = V_2 / V_1$. Figure 4 shows the potential well shape with different harmonic voltage ratio. Figure 4 shows that -0.5 is the best harmonic voltage ratio to get the widest and flattest potential well.

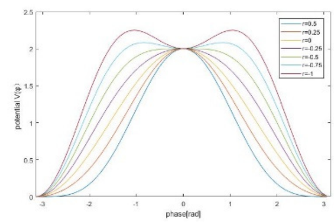

Figure 4: The shape of the potential well varies with the phase under different harmonic voltage ratios.

The bucket of the longitudinal phase space is drawn in the case of single RF wave and dual harmonic wave, as shown in Fig. 5. It can be seen that the bucket region is elongated after using dual harmonic, and the area of stable motion of particles increases, which can play a role in improving the capture and acceleration efficiency [4].

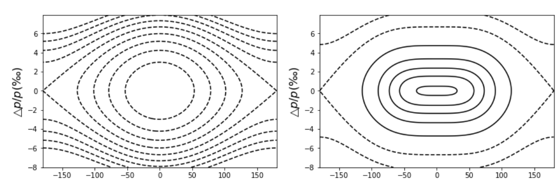

Figure 5: The bucket region under single (left) and dual (right) harmonic.

EXPERIMENTAL RESULT

After designing the parameters related to radio frequency system of the synchrotron, we carried out the beam tuning experiment on the XiPAF to capture and accelerate the 7 MeV proton beam injected from the linear accelerator. In the experiment, DCCT (direct-current current transformer) was used to measure the change of current intensity. According to the collected data, the capture and acceleration efficiency and the loss rate of proton beam can be obtained. A typical single harmonic capture acceleration result is shown in Figs. 6 and 7. The

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green line marks the time (10 ms) when the capture process ends. During the capture and acceleration process, the DCCT current intensity increases from 21 mA to 35 mA, and the capture acceleration efficiency is about 60%. The loss is mainly due to a large number of protons are not in the bucket at the initial stage and the range of energy dispersion is large. During acceleration process, there is a large current loss rate at around 260 ms, which is mainly caused by the interference of DCCT signal. The current loss rate at other times during acceleration is all lower than 2‰.

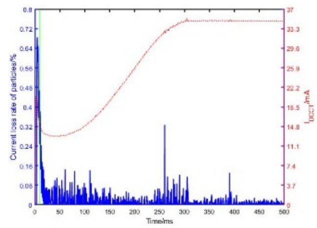

Figure 6: Current lose rate of particles and DCCT current intensity over time (single harmonic).

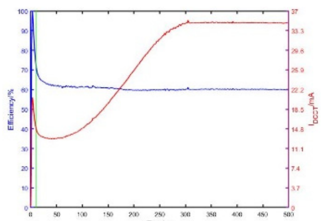

Figure 7: Capture and acceleration efficiency and DCCT current intensity over time (single harmonic).

The experiment with dual harmonic was also observed. The result is shown in Figs. 8 and 9. In the process of capture and acceleration, the current intensity of DCCT increases from 20 mA to 38 mA, and the overall efficiency is 67%, which is 7% higher than that of the single harmonic. It is mainly due to the fact that the bucket of dual harmonic is flatter than that of single harmonic.

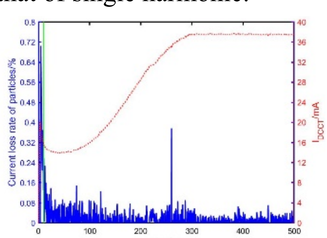

Figure 8: Current lose rate of particles and DCCT current intensity over time (dual harmonic).

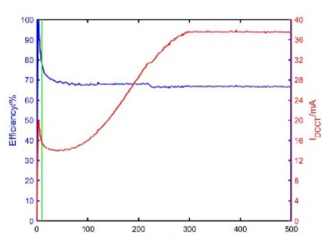

Figure 9: Capture and acceleration efficiency and DCCT current intensity over time (dual harmonic).

EXPERIMENTAL AND SIMULATION RESULT

The capture processes under different maximum cavity voltages were simulated. During the experiment, we have done the capture and acceleration experiments under different maximum cavity voltages. Figure 10 shows the efficiency under different situations. The capture efficiency decreases with the increase of the maximum RF voltages. The acceleration efficiency increases with the increase of the maximum RF voltages. The highest overall efficiency happens at 600 V.

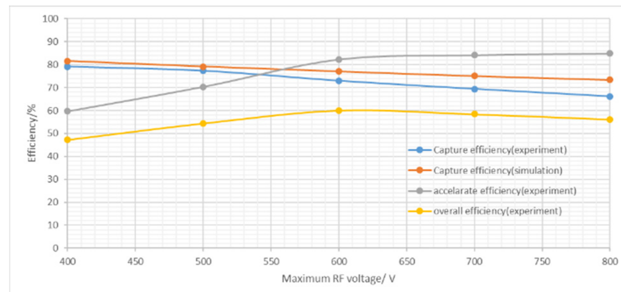

Figure 10: The efficiency under different maximum voltages.

The decrease of capture efficiency with the increase of the maximum voltages may be related to the increasing of the maximum momentum dispersion of bucket, which leads to the decrease of transverse acceptance and the transverse loss of particles. Figure 11 illustrates this performance. The blue line shows the maximum momentum dispersion of bucket increasing, and the red line shows transverse acceptance decreasing.

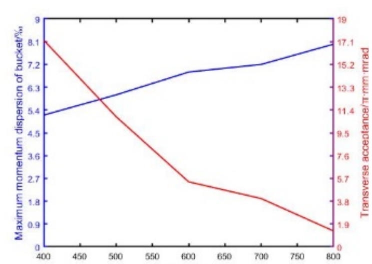

Figure 11: The maximum momentum dispersion of bucket and transverse acceptance under different maximum voltages.

CONCLUSION

In order to improve efficiency, dual-harmonic was used during capture and acceleration process. During the experiment, the capture efficiency was increased by 5%, and the acceleration efficiency was increased by 4%.

The capture efficiency decreases with the increase of the maximum RF voltages. The acceleration efficiency increases with the increase of the maximum RF voltages. The highest overall efficiency happens at the maximum 600 V RF voltage.

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