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INJECTION OPTIMIZATION AND STUDY OF XiPAF SYNCHROTRON

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Abstract

The synchrotron of XiPAF (Xi'an 200 MeV proton application Facility) is a compact proton synchrotron, which using H^- stripping injection and phase space painting scheme. Now XiPAF is under commissioning with some achievements, the current intensity after injection reach 43 mA, the corresponding particle number is 2.3×10^{11}, and the injection efficiency is 57%. The simulation results by pyORBIT show that the injection efficiency is 77%. In this paper, we report how the injection intensity and efficiency were optimized. We analyzed the difference between simulation and experiments, and quantitatively investigate the factors affecting injection efficiency through experiments.

INTRODUCTION

Xi'an 200 MeV Proton Application Facility (XiPAF) is a basic scientific research platform for proton space irradiation research [1, 2], located in Xi'an, China. The main part of the XiPAF machine is a synchrotron with a circumference of 30.9 m, with stripping injection of 7 MeV negative hydrogen ions. Designed injection current is 5 mA and accumulated particle number is 2×10^{11} after injection. After injection, the longitudinal adiabatic capture is carried out, then the beam is accelerated and extracted (Table 1).

Table 1: Synchrotron Design Parameters

Parameters	Injection	Extraction
Particle Number	2×10^{11}	1×10^{11}
Tune ν_x/ν_y	1.72/1.79	1.68/1.76
Chromaticity ξ_x/ξ_y	-0.25/-2.32	-0.21/-2.27
Max β_x/β_y [m]	5.9/6.1	5.7/6.0
Max D_x/D_y [m]	2.5/0.0	2.6/0.0

The XiPAF injection system consists of an injection magnetic septum, stripping foil, two bump magnets and three Chicane magnets [3]. The stripping foil size is 15 mm × 30 mm, centered in the horizontal direction, and 72 mm away from the horizontal reference orbit. Horizontal phase space painting is realized by reducing the strength of the injection bump magnets, which increases horizontal emittance to reduce the space charge effect [4], also, reduces the number of beam passes through the stripping foil for lower beam loss caused by the stripping foil.

Since the formal workshop has not been completed, the beam commissionning is carried out in a temporary workshop. Due to the limitation of the radiation shielding, the extraction energy is set to 60 MeV during commissioning. We will introduce how we optimize injection and capture efficiency, and analysis the difference between simulation and experiments.

MEASUREMENT

We integrate the FCT signal to obtain the injection beam current curve for optimization.

Assuming that the FCT signal attenuation is exponential, the time constant τ and the signal attenuation ratio Δ between two adjacent sampling points can be calculated

$$\Delta = 1 - \exp\left(-\frac{1}{f_s \tau}\right), \quad (1)$$

where f_s is the sampling frequency, τ is the attenuation time constant of the FCT signal. Assuming that the original beam current signal is I_{Beam} and the beam current signal measured by FCT is I_{FCT}, the relationship between two signal mentioned above can be written as

$$I_{FCT,i+1} = I_{FCT,i}(1 - \Delta) + I_{Beam,i+1} - I_{Beam,i} \ , \quad (2)$$

where i represents the i-th sampling point. So the original beam current signal can be calculated point by point

$$I_{Beam,i+1} = I_{Beam,i} + I_{FCT,i+1} - I_{FCT,i}(1 - \Delta). \quad (3)$$

Injection efficiency η_{inj} and gain G_{inj} can be calculated as

$$\eta_{inj} = \frac{I_{inj}T}{I_{MEBT}t_{inj}}, \quad G_{inj} = \frac{I_{inj}}{I_{MEBT}} , \quad (4)$$

where I_{inj} is beam current after injection, T is revolution period, I_{MEBT} is MEBT beam current, t_{inj} is injection time, i.e. MEBT beam pulse width.

Capture current is hard to determined. DCCT current at 10 ms consists of two part of particles, which is captured particles in the RF bucket and flowing particles outside the RF

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bucket. Flowing particles cannot be captured and will lose during acceleration. Beam current of caoptured particles is real capture current.

FCT signal waveform represents the longitutional beam distribution after capture. If we use WCM to measure captured beam current, we could get similar waveform but the minimum current shifted to zero. This current shift is DC part of capture current waveform, so we use this current shift as capture current for capture efficiency calculation.

Capture efficiency η_{cap} can be calculated as

$$\eta_{cap} = \frac{I_{cap}}{I_{inj}}, \tag{5}$$

where I_{inj} is beam current after injection, I_{cap} is capture beam current.

OPTIMIZATION

Injection and capture optimization is carried out. First, we match beam energy, dipole strength and RF frequency for higher acceleration efficiency, then we fix dipole strength and RF frequency parameters for injection optimization.

Capture

By selecting one closed orbit, synchronously adjust the RF frequency and the dipole strength to keep the closed orbit unchanged, the synchronous energy under this closed orbit can be changed. During the adjustment process, when the beam energy and the synchronous energy is matched, the maximum capture efficiency under this closed orbits can be obtained.

Since the beam pipe at the extraction magnetic septum MS01 are asymmetrical, the pipe inner width is 42 mm, and outer width is only 22 mm, which is the main limit of XiPAF synchrotron acceptance. A closed orbit shift at MS01 can increase acceptance and improve the efficiency of injection and capture.

A easy way to shift closed orbit is change the dipole strength. We choose a set of orbits, and at each orbit we adjust dipole strength and RF frequency synchronously as mentioned above, without correctors, a maximum capture efficiency of 51% is obtained.

Another solution is a local bump orbit at MS01. Horizental correctors are used and their strength are optimized to obtain higher beam curret and efficiency. Optimazition give a total injection efficiency of 21% and a capture efficiency of 65%.

Injection

We found a exponential bump waveform is helpful for a higher injection efficiency, as shown in Fig. 1.

By changing two bump strength raughly, the maximum current after injection of 47 mA is achieved, corresponding to the particle number 2.5×10^{11}, with MEBT current of 1.1 mA, the total injection efficiency reaches 58%, the single turn maximum injection efficiency is 80%, and the total

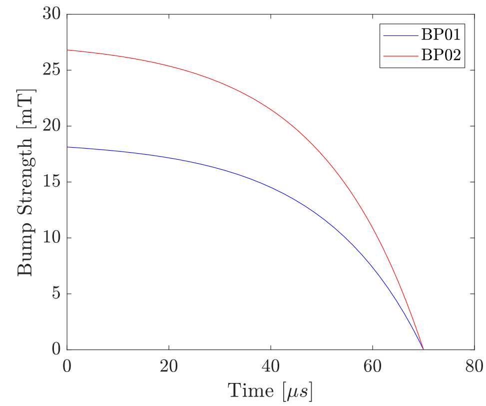

Figure 1: Injection bump megnet curves.

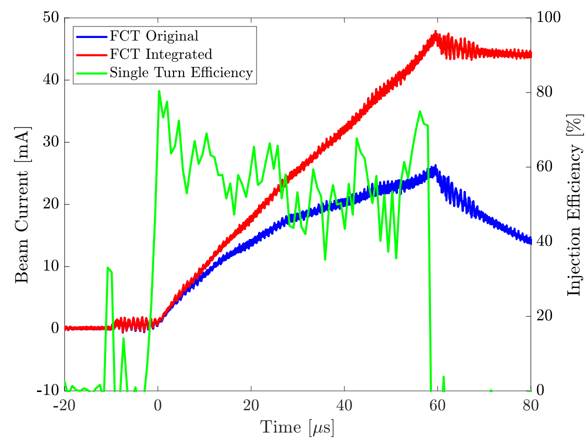

Figure 2: Injection current curve and single turn injection efficiency curve.

injection gain is 41. Fig. 2 shows FCT signal and injection current curve.

Due to equipment problems, MEBT beam pulse width is limited at 40 µs. FCT signal amplifier is equipped to reduce signal noise. Stripping foil is a little broken which means some negative hydrogen ion can not be stripped to proton, and injection efficiency is lower than before, even in the same synchrotron parameters. Further optimization is taken in this condition.

Scanning the strength of the two injection bump magnets respectively, the optimal bump strength value is obtained: BP01 is 13.8 mT and BP02 is 20.4 mT. Beam current after injection is 37.4 mA, corresponding to the number of particles 2.0×10^{11}, and the injection efficiency is 54%. The scan result is shown in the Fig. 3.

Set BP01 strength 16.2 mT and BP02 strength 26.1 mT. Considering the time when beam start to be injected into the synchrotron ring is fixed, phase space painting can be changed by setting different injection bump delay.

The relationship between the injection efficiency and the injection bump magnet delay is calculated by pyORBIT simulation. Bump delay represents injection bump magnet trigger time. If the bump delay is 1 295 µs, MEBT beam

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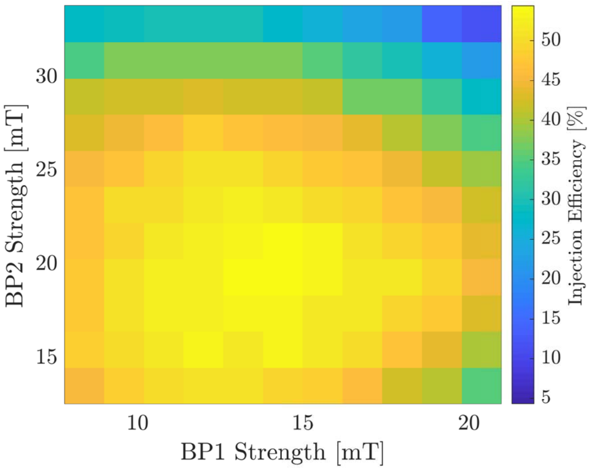

Figure 3: Injection bump strength scan.

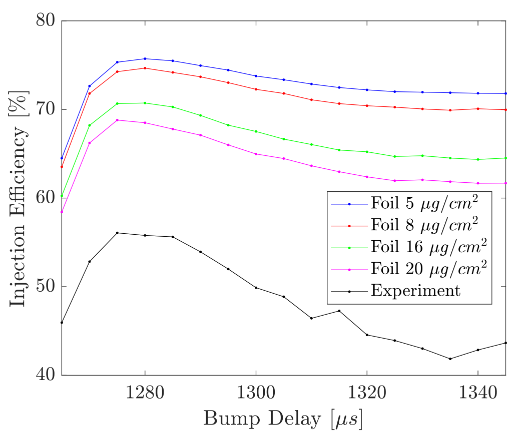

Figure 4: Injection bump delay scan.

inject into synchrotron ring at just the time when bump magnetic field start to drop from top. If bump delay is larger than 1 295 µs, some particles will be injected at bump top. Simulation curves and experiment curve have the similar shape, but the simulation results give higher efficiency.

DISCUSS

Stripping Foil

It was found in the experiment that the stripping foil quality has a great influence on the injection efficiency, the foil quality is quite different even in same specification. It's hard to simulate the influence of used foil in the experiment.

According to the data in Fig. 2, the maximum total injection efficiency of negative hydrogen ions in a single revelotion period is 80%, so the total transport efficiency and the receiving efficiency of the stripping foil are not less than 80%. Since the actual stripping efficiency is not convenient for direct measurement, if it is assumed that the receiving and stripping efficiency of the stripping foil is 85%, this means that when the total injection efficiency is 58%, the beam accumulation efficiency during injection is 68%, which is less than the simulated efficiency of 77%.

Simulation results in Fig. 4 have take the receiving and stripping efficiency into considieraton. Comparing the results in Fig. 4, there is about 20% difference between simulation and experiment. This may comes from lattice model, broken foil and MEBT beam phase space distribution which is difficult to measure.

Injector

Injector parameters affect beam energy and phase space distribution. After injector optimization, we got higher injection efficiency, the injection current curve is shown in Fig. 5. Injection efficiency reaches 70%, the beam current at 40 µs is 47 mA when the injection is just finished, and the current at 200 µs is 38 mA which is a little smaller than DCCT maximum current 42 mA at injection. This is a powerful proof that our FCT signal integration algorithm is correct. But, at this situation, capture current is just 10 mA and current after acceleration is just 6 mA, this problem may comes form strong space charge effect.

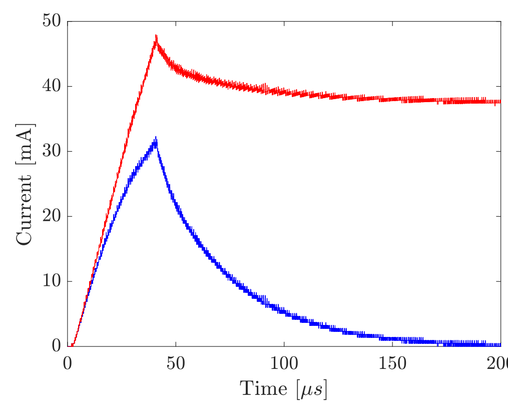

Figure 5: Injection current curve after adjustment of injector.

In order to further improve the injection efficiency, optimization can be carried out in two aspects: (1) the optimization of the MEBT beam distribution [5]; (2) the optimization of Lattice optical parameters during injection, including tune and closed orbit. More experement should be done about space charge effect and stripping foil effect.

CONCLUSION

This article introduces the XiPAF injection commissioning results. Particle number after injection can reach 2.5×10^{11}, and the total injection efficiency can reach 58%. With new injector parameters, total injection efficiency can reach 70%. Analysis has been done by comparing results from experiment and simulation. More optimization and study should be done in XiPAF to reduce beam loss and increase efficiencies.

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