H- CHARGE EXCHANGE INJECTION FOR XiPAF SYNCHROTRON

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Abstract

The physics design of the H^- charge exchange injection system for Xi'an Proton Application Facility (XiPAF) synchrotron with the missing dipole lattice is discussed. The injection scheme is composed of one septum magnet, three chicane dipoles, two bump magnets and one carbon stripping foil. A 7 μg/cm^2 carbon foil is chosen for 7 MeV H- beam for high stripping efficiency and low coulomb scattering effect. The simulation results of the horizontal and vertical phase space painting finished by two bumper magnets and mismatching respectively are presented.

INTRODUCTION

Xi'an Proton Application Facility (XiPAF) is under construction in Xi'an, China, to fulfil the need of the experimental simulation of the space radiation environment, especially for the research of the single event effect (SEE). XiPAF is mainly composed of a 7 MeV linac injector, a synchrotron (60~230 MeV) and two experimental stations. The synchrotron [1] has a 6-fold "Missing-dipole" FODO lattice with its circumference of 30.9 m, the focusing structure consists of 6 dipoles and 12 quadrupoles, and six 2.21 m long drift space is left for accommodation of injection, extraction and acceleration system etc. The stripping injection method is chosen to achieve higher beam intensity of 2×10^{11} proton per pulse (PPP). And the phase space painting is chosen to control the space charge effect. The parameters from the linac injector are shown in Table 1.

Table 1: Injection Parameters for XiPAF Synchrotron

Parameter	Value	Unit
Injection ion type	H^-	
Beam energy	7	MeV
Peak current	5	mA
Maximum repetition rate	0.5	Hz
Beam pulse width	10~40	μs
Normalized RMS emittance	~0.25	π mm·mrad
Injection period	0.85	μs
Number of particles	2×10^{11}	

INJECTION LAYOUT

The layout of injection system for XiPAF synchrotron is shown in Fig.1, a carbon strip foil near the center of the injection section and three DC chicane dipoles (CH1, CH2, CH3), are arranged in the injection section; and two bumper magnets (Bump1, Bump2) located in the two sections adjacent to the injection section.

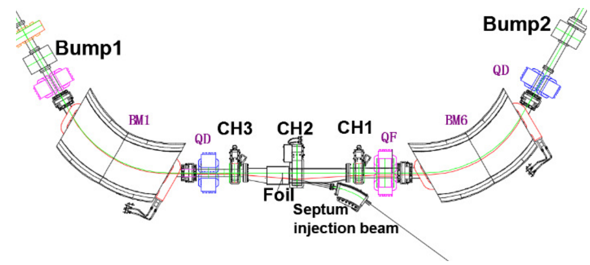

Figure 1: Injection Layout of XiPAF synchrotron.

In order to inject the beam properly, the closed orbit need to be bumped to the position of the strip foil during the beam injection. Three DC Chicane dipoles produce a fixed bump in the closed orbit near the strip foil. Then two bumpers are switched on to bend the closed orbit an additional 2.4 cm outward, and to make the closed orbit passing through the strip foil so that the injected beam and circulating beams overlap. The closed orbit bump produced by three chicane dipoles and two bumpers is shown in Fig.2.

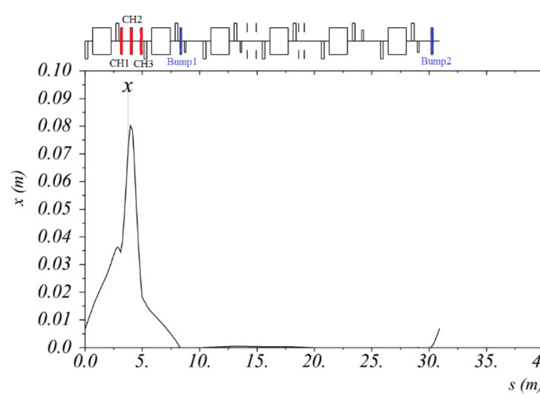

Figure 2: The closed orbit bump.

Table 2: Main Parameters of Chicanes and Bumpers

Parameter	CH1	CH2	Bump1	Bump2
Kick angle (mrad)	70	140	10	7
Magnetic field (T)	0.17	0.28	0.024	0.017
Effective length(mm)	150	200	160	160

The main parameters of three chicane dipoles and two bumpers are given in Table 2. The parameters of CH3 are same with the ones of CH1. During injection, 7 MeV H^- beam is converted to protons by the strip foil. After the injection, the two bumpers are switched off to move the closed orbit off the strip foil completely.

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ISBN 978-3-95450-178-6

STRIPPING FOIL

For XiPAF synchrotron, H^- charge exchange injection method is adopted to achieve high intensity. At end of the second chicane, there is a carbon stripping foil on the path of injection. H^- particles are stripped two electrons and converted to protons by the carbon strip foil in the injection. The thickness of carbon stripping foil is chosen from two aspects to consider, the foil should be thick enough to strip two electrons of H^- while the emittance growth caused by it is acceptable.

When H^- particles enter the foil, electrons of the particle can be stripped away or the particle can capture electrons from atoms in the foil. The fraction of H^-, H^0, H^+ can be calculated using the formula [2] as following:

$$N^- = e^{-(\sigma_{-10}+\sigma_{-11})x}$$
$$N^0 = \frac{\sigma_{-10}}{\sigma_{-10}+\sigma_{-11}-\sigma_{01}}[e^{-\sigma_{01}x} - e^{-(\sigma_{-10}+\sigma_{-11})x}]. \quad (1)$$
$$N^+ = 1 - N^- - N^0$$

Where N-, N0, N+ are the three charge fractions, x is the number of target atoms per cm^2, σ_{-10}, σ_{01}, σ_{-11} are the electron loss cross sections. The measurements of these cross sections for H- in carbon have been obtained by Gulleyet al. [3] at 800MeV as

$$\sigma_{-10} = (6.76 \pm 0.09) \times 10^{-19}\ cm^2$$
$$\sigma_{01} = (2.64 \pm 0.05) \times 10^{-19}\ cm^2 \quad (2)$$
$$\sigma_{-11} = (0.12 \pm 0.06) \times 10^{-19}\ cm^2.$$

Then we can evaluate three cross sections for 7 MeV H^- in carbon, and calculate the stripping efficiency, that is fraction of H^+ for several different thickness foils, the results are listed in Table 3. Where l is the thickness and η is stripping efficiency; $\Delta\varepsilon_{rmsx}$, $\Delta\varepsilon_{rmsz}$ and $\Delta\delta_{rms}$ are rms emittance growth in horizontal and vertical direction, and momentum spread increase respectively, the data in these three columns is multiplied by 10, which means passing through the foil 10 times.

Table 3: Results of stripping efficiency, emittance growth and momentum spread increase vary with foil thickness.

l ($\mu g/cm^2$)	η (%)	$10\Delta\varepsilon_{rmsx}$ (πmm·mrad)	$10\Delta\varepsilon_{rmsz}$ (πmm·mrad)	$10\Delta\delta_{rms}$ (%)
5	93.4	0.91	0.79	0.02
6	96.5	1.09	0.95	0.024
7	98.1	1.27	1.11	0.028
8	99.0	1.45	1.27	0.031

From the results in Table3 we can see that stripping efficiency increases with the foil thickness, but the foil cannot be too thicker, because when the beam passes through the foil, the coulomb scatterings cause the emittance and the momentum spread to increase, and thicker foil means larger emittance and momentum spread growth. The emittance growth and the momentum spread increase of passing through strip foil are given in formula (3) and (4) respectively [4]

$$\Delta\epsilon_y = 58.87\frac{\beta_y[m]}{\beta^2(pc[MeV])^2}\frac{l[\mu g/cm^2]}{X_0[g/cm^2]} \quad (3)$$

Where $\Delta\varepsilon_y$ denotes emittance growth for horizontal direction x or vertical direction z, β_y is β function value at the strip foil for horizontal direction x or vertical direction z, l is thickness in $\mu g/cm^2$, the radiation length X_0 is 42.97 g/cm^2 for carbon.

$$\Delta\delta = \frac{\Delta E}{\beta^2 E} = \frac{KZz^2}{A\beta^4 E}\left[ln\frac{2m_e c^2\beta^2\gamma^2}{I} - \beta^2\right]l \quad (4)$$

Where K=0.307 MeV/(g /cm^2) is a constant, me is the rest mass of electron, Z and A are the atomic charge and mass number of the foil, $I=16Z^{0.9}$ is the effective ionization potential of the medium atom. The rms emittance increase and the momentum spread growth due to multiple coulomb scattering are calculated and shown in Table 3.

From the injection simulation results given at the next section we know the average hits number per proton is about 6, at Table3 we use 10 hits number with enough margin to do the calculation. From the linac injector with a debuncher the beam momentum spread is ±0.45% and the acceptance of the ring is ±0.7%, so the thickness of 5~8 $\mu g/cm^2$ can be acceptable.

The thickness of 5 $\mu g/cm^2$ foil is about 25 nm, even the 8 $\mu g/cm^2$ foil is only 40 nm, these foils cannot be self-supporting, they are made on glasses. The size of foil is 15 mm (width)×30 mm (height), the "U" shape frame with three supported edges and one free edge is used to support the foil. We did several experiments and now three thickness foil of 5 $\mu g/cm^2$, 7 $\mu g/cm^2$, 8 $\mu g/cm^2$ are successfully moved on to the "U" shape frame from the glasses, Fig.3 shows the picture of 5 $\mu g/cm^2$ and 8 $\mu g/cm^2$ foils.

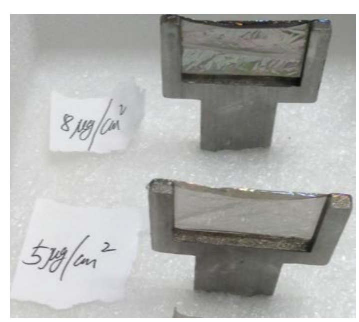

Figure 3: The "U" shape frame with foils.

From our experience, the foil is thicker and the success rate of the experiment is higher. Based on the above factors, the thickness of 7 $\mu g/cm^2$ is chosen, which provides more than 98% stripping efficiency while the emittance growth and momentum spread increase remain acceptable.

PHASE SPACE PAINTING

XiPAF synchrotron requires 2×10^{11} proton per pulse injected into the ring, so the phase space painting method is adopted. The injected beam is painted into the large transverse phase space to reduce the influence of space charge effects. As shown in Fig.1, two bumpers make a time dependent bump orbit for beam painting in horizontal plane. As for the vertical plane, the phase space painting is realized by phase space mismatching, at the same time an off-center coordinate at the injected point in vertical phase space is used for more uniform distribution after painting.

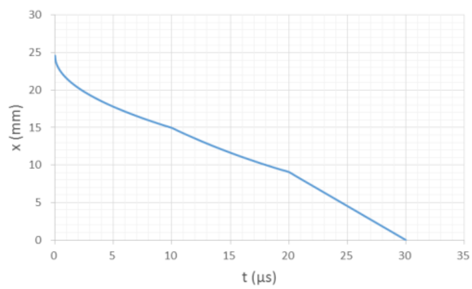

Figure 4: The orbit bump moving curve.

We have simulated the phase space painting using ORBIT [5] code and the space-charge effects have been taken into account. About the moving curve, we did a lot of calculations using square-root function, exponential function and linear function. After the optimization the orbit bump moving curve is given in Fig.4, which is a piecewise function and the falling down time is 30 µs. The injected beam is painted in two phase space to control the tune shift under 0.2. Two dimension plots in horizontal phase space (x, P_x), vertical phase space (z, P_z) and in real space (x, z) are given in Fig.5 at different turns.

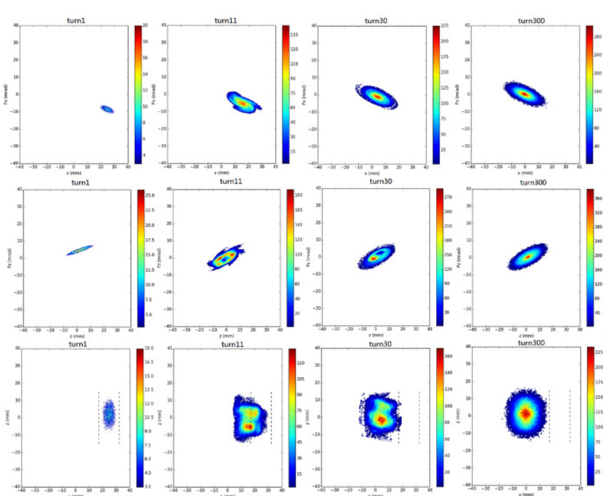

Figure 5: Phase space and real space distribution at different turns (the three rows are (x, P_x), (z, P_z), and (x, z) respectively; the four columns are turn 1, turn 11, turn 30 and turn 300 respectively).

The rms emittance of 7 MeV injected beam is 2 π mm·mrad, after the transvers phase painting the rms emittance is shown in Fig.6, 2×10^{11} proton can be obtained after 11 turns injection, and the average number of hits on the foil per proton is 6 before the circulating beam keep away from the foil.

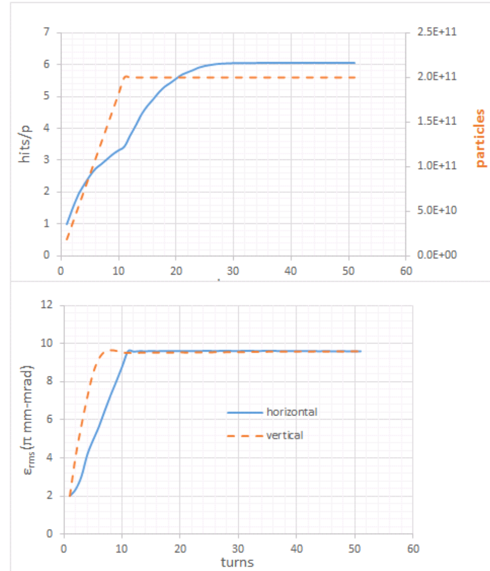

Figure 6: The hits number on the foil and the rms emittance after phase painting.

CONCLUSION

The 7 MeV H^- charge exchange injection system has been designed for Xi'an Proton Application Facility. The 15 mm (H)×30 mm (V), 7 µg/cm^2 foil is chosen to provide more than 98% stripping efficiency, the emittance growth and momentum spread increase are acceptable; the foil has been successfully moved to the "U" shape frame. 2×10^{11} particles per pulse are injected into the synchrotron using the phase painting method. At present the bumpers, chicane dipoles and stripping foil system are under construction.

ACKNOWLEDGEMENT

The authors would like to thank Dr. J. Qiu and X. Y. Zhang for the guidance of using ORBIT code.

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ISBN 978-3-95450-178-6