STUDY OF THE BEAM INJECTION AND EXTRACTION OF THE PROTON IRRADIATION ACCELERATOR

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Abstract

The proton irradiation accelerator is widely founded for industry application, and the extracted beam is required to have large intensity as a pulse beam or uniform distribution for scanning. A multi-turn injection is adopted and the proton beam is injected into the ring with the energy of 10MeV. In order to increase injection beam intensity and make the injection beam more uniform, the injection bump height is optimised. Furthermore, for considering the extracted beam, or so called the spill, with satisfied uniform distribution, A RF knock-out method is used for slow extraction with third order resonance. The sextuple's strength and location are well studied for the efficiency of the extraction. Also the RF kicker's amplitude is well optimised during the whole extraction period.

INTRODUCTION

Many proton irradiation synchrotron accelerators are widely used with the development of the industry. And the beam injection and extracted are vital important for the accelerator performance. A proton cycling synchrotron, which was designed to accelerate and accumulate the protons injected by the tandem Linac in the energy of 10MeV, and after the energy reached to 300MeV, the beam will be extracted slowly and totally by the third order resonance method. For considering the space limitation, multiple multi-turn injection with 2-bump was adopted. And the Main parameters of the irradiation proton accelerators are listed in Table 1.

Table 1: Main parameters of irradiation proton accelerator

Parameters	Units	Values
Circumference	m	33.6
Inj. Energy	MeV	10
Ext. Energy	MeV	300
Nominal Tunes(H/V)		1.66/1.20
Injection turn number		22
Injection beam emittance (rms)	πmm-mr	6.8317
Injection beam current (DC mode)	μA	100

Third order resonance method is a common technique for better control of the extracted beam characters. When the horizontal tune of the beam is near $n \pm 1/3$ (n is a random integer), some particles far away for the beam core may become unstable, because the sextuples in the ring can establish a limited stable area in the shape of triangle. In order to control the extracted beam more precisely, a RF knock off method was adopted to make the particles amplitude growth beyond the triangle. The RF kicker's amplitude should be carefully modified during the period of the extraction to make the extraction beam more flatten.

OPTIMISITION OF THE INJECTION BUMP HEIGHT DECREASE PATTERN

The Lattice of the proton irradiation synchrotron is designed with four super-period, and the beta functions are all below 4 m. The layout and the beta functions of the Lattice are shown in figure 1. Two kickers whose phase advance equals π are located summarily in the injection region to make an orbit bump towards the injection beam. Two RF kickers are also located in this area for the excitation of the beam. There are four spaces are reserved for sextuples, and two of which are located in the dispersion free region for producing the driving term and the other two are located in the arc area for compensation of the chromaticity. The layout of the Lattice and the twiss parameters are shown in Figure 1. Firstly, the bump height was set at a maximum value, and then the bump height decreased in every turn. Figure 2 shows the injection bump in the first turn and the beam distribution after the injection was completed.

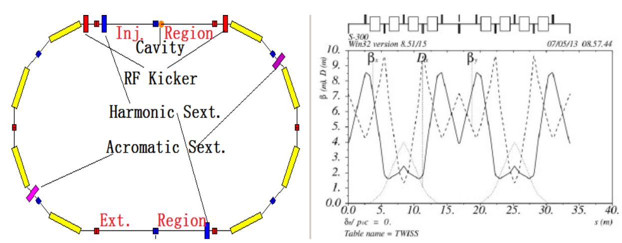

Figure 1: The layout of the irradiation proton synchrotron and the twiss parameters of the lattice of the synchrotron.

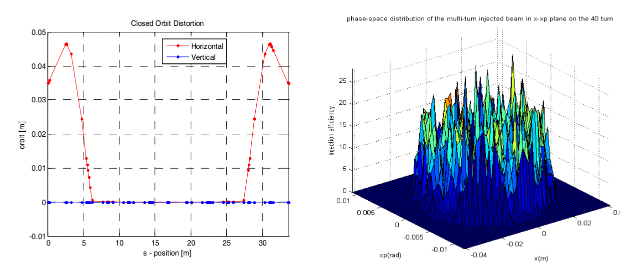

Figure 2: The orbit bump in first turn and the beam distribution after the injection process is completed.

In order to get a uniform distribution of the beam, the bump height is always designed to decrees in a square root pattern, that means the injection bump is decreasing

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in this pattern, $x = x_{\max} - (x_{\max} - x_{\min})\sqrt{\frac{t}{t_{inj}}}$ [1], where x is the bump height. However, after series simulations, the square root pattern is not the best choice to get the most uniform distribution. The left part of figure 3 shows the decrees patterns of fitting curve and square root curve. By using the fitting curve, not only more uniform distribution can be gotten, and also more particles can be injected into the ring. The right part of the Figure 3 represents the protons accumulated during the injection process. The maximum accumulated protons were reached approximate to 13500 at the 22th turn, and then decreases to 10000 at the 31th turn, that because the protons hit the septum and make the beam loss. And then, the accumulated protons keep stable.

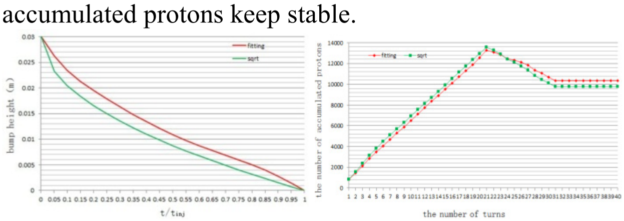

Figure 3: Left part: injection bump height decreases pattern versus injection turn; Right part: the numbers of accumulated protons versus number of turn in the injection period. The red line and green line correspond to the fitting curve and square root curve respectively.

PLANING SEXTUPOLE FAMILIES FOR BEAM EXTRACTION

The third-order resonance can be used to extract particles from a synchrotron over a large number of turns. And the slowly extracted beam is known as spill [2]. When the particles tunes are near to $n \pm 1/3$ (n is a random integer), the sextuples can separate the phase space into stable region and unstable region. The left part of Figure 4 shows 9 particles with different initial position revolution 100 turns. And from the figure, the particle in the outer space became unstable and the amplitude grew bigger and bigger, however, the other particles still keep stable in the inner area. For describing the third-order resonance more precisely, the distance h between the upright separatrix and the upright axis (X') is conveniently introduced. Where $h = \frac{2}{3}\frac{\varepsilon}{S} = \frac{4\pi}{S}\delta Q$, and ε or δQ is tune distance between particles and third-order resonance, and S is the normalized sextuple strength [2].

In our simulation, two sextuples were placed in the synchrotron, and one is located in the third period in the dispersion area, the other is located in the second period in the dispersion free area. Firstly, we adjust the chromatic sextuples and make the horizontal chromaticity equal -0.0006, and value of the normalised sextuples strength is -24.0826 m$^{-1/2}$. And then the harmonic sextuple was placed in the second region, and the phase advance between two sextuples is $\pi/3$. By using Accelerator Toolbox [3], we can get distance h, and the comparison between theoretical calculation and the numerical tracking is listed in Table 2. From the table, the distance h between theoretical computation and numerical tracking are agreed well. For considering saving the sextuple strength, two sextuples whose phase advance is $\pi/3$ are enough to extract the spill from the synchrotron.

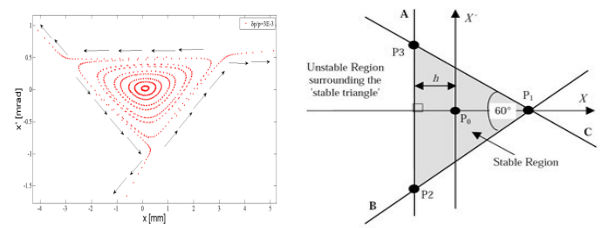

Figure 4: left: stable region and unstable region for the numerical tracking. Right: the theoretical analysis diagram of the third-order resonance.

Table 2: The distance h comparison between the theoretical value and numerical tracking

	1	2	3	4	5	6
Chromatic sext.	S	S	S	S	S	S
Harmonic sext.	0	-S	-2S	-3S	-4S	-5S
Theoretical h [m$^{1/2}$]	0.00 347 9	0.00 178 5	0.00 116 0	8.69 67E- 4	6.95 73E- 4	5.797 8E-4
Numerical tracking h [m$^{1/2}$]	0.00 320 5	0.00 162 8	0.00 108 1	7.92 17E- 4	6.49 78E- 4	5.326 4E-4

RF KNOCK-OFF METHOD FOR SLOW EXTRACTION

RF knock-off method can provide high irradiation accuracy even for an irregular target, and result in high beam-utilization efficiency. And also RF knock-off method is useful in the spot scanning method, because the beam supply can be easily started or stopped in the extraction period [4]. RF kicker is a dipole which can provide the transverse kick with related to the beam tune Q_x. After the separatrix is fixed, the RF knock-off method can make the beam emmittance growth and then the beam can be extracted. Figure 4 shows a particles position versus the revolution turn in 4 different RF modulation rate, the modulation rate are 0.34, 0.341, 0.342, and 0.343 respectively, and the particles tune are all equalled to 1.66. So a mono frequency of the RF kicker can not to be used to extract much particles in the synchrotron, and then some other technique, like amplitude modulation (AM), frequency modulation (FM) are used to smooth the spill.

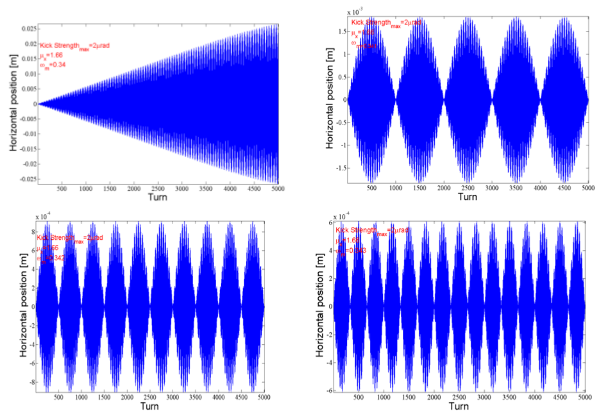

Figure 4: One particles position versus revolution turn correspond to different RF kicker modulation rate. The particles tune is 1.66, while the modulation rate is 0.34, 0.341, 0.342, and 0.343 respectively.

For a uniform distribution beam containing 1000 particles, A RF kicker is used to excite the beam in 1000 turns. The number of extracted particles is 652, and the spill structure is shown in figure 5. By using a Rayleigh distribution function to fit he spill, the results are satisfied.

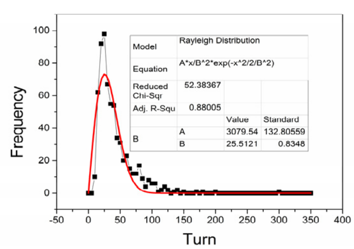

Figure 5: The spill character extracted from a uniform distribution beam.

For a Gaussian distribution beam in the normalized phase space coordinate (X, X'), the radial distribution function of particles can be expressed by using the Rayleigh distribution function as $p(r)=\frac{2r}{\sigma^2}\exp[-\frac{r^2}{\sigma^2}]$ [5], where σ is the standard deviation of the Rayleigh distribution. The time structure of extracted beam can be represented as $\frac{dN_{ext}}{dn}=N_0\frac{d\sigma^2(n)}{dn}\frac{r_0^2}{\sigma^4(n)}\exp[-\frac{r_0^2}{\sigma^2(n)}]$, where r_0 is radial amplitude for extraction. In order to get a flat beam and to extract all the particles in the ring, the AM functions of the RF kicker can be expressed as

$$\theta(n)=[\frac{d}{dn}(\frac{\sigma^2(n)}{k})]^{1/2}, \quad (1)$$

where k is a constant number related to the growth of the standard deviation σ of Rayleigh distribution versus to revolution number n, and

$$\sigma^2(n)=-r_0^2[\ln[\frac{n}{f_{rev}\tau_{ext}}\{1-\exp(-\frac{r_0^2}{\sigma_0^2})\} + \exp(-\frac{r_0^2}{\sigma_0^2})]]^{-1}. \quad (2)$$

Where τ_{ext} is the total extraction time, and is equals to 1.6ms in our simulation Figure 6 shows the RF kicker's strength versus the revolution number.

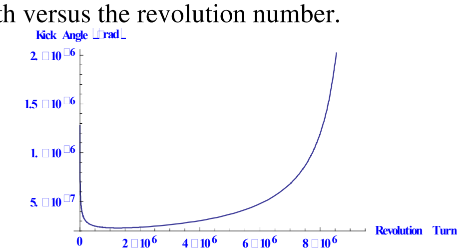

Figure 6: The RF kicker's strength versus the revolution number

CONCLUSION

A radiation synchrotron with circumference of 33.6 has been designed. A multi-turn injection method with 2-bump is adopted for beam injection. And the injection bump height is carefully optimised to make the distribution of the injection beam more uniform in normalised phase space. A RF knock-off method with amplitude modulation is used to smooth the spill. For considering saving the strength the sextuples, the combination of two sextuples with different strength whose phase advance is $\pi/3$ has been carefully studied, and one can conclude that sextuples with $\pi/3$ phase advance with the opposite polarity enforce the driving term of the third order resonance, and it is very useful for the sextuple planning in a small proton accelerators.

ACKNOWLEDGEMENTS

The author would like to thank Manzhou Zhang in SSRF for his help discussion in the slow extraction with third order resonance.

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