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SLOW EXTRACTION STUDY BY USING SEXTUPOLE

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Abstract

The spill continuously extracted from synchrotron by using resonance sextupoles plays a key role in multidisciplinary application. The intensity of virtual sextupole and the spiral step for the typical synchrotron are obtained theoretically. To study the beam loss, a customized synchrotron with different extraction layouts is designed and the tracking code of slow extraction is developed. The result shows that the beam losses at extraction point are different for three cases and it is advantage to beam loss for extraction components placed in dispersion-free straight section.

INTRODUCTION

Molecular biology, single particle effect in electric components and cancer therapy using proton beam has been highlighted because of relative biology effectiveness and small beam diffraction. A proton synchrotron complex has being constructed in the world [1] - [5]. The proton synchrotron is to provide the proton beam with smooth spill, reliability and simplicity of operation. The beam generally continuous extracted by using three-order slow extraction method with RF excitation, which typically needs a resonance excitation sextupole (RSEX), RF knock-out (RFKO), an Extraction Electrostatic Septum (EES) and a Magnetic Septum (EMS).

In the synchrotron with extraction fraction tune of ±π/3, one or two RSEXs and two chromaticity sextupoles are typically designed [6]. A RSEX is placed in dispersion-free straight section or two RSEXs with anti-equal intensity are placed in dispersion section at symmetrically opposed positions so that they can be used without affecting the chromaticity. Two chromaticity sextupoles with equal intensity are placed in each arc symmetrically so as to not affecting the resonance excitation. In fact, the extraction fraction tune with small different from ±π/3, resonance excitation and chromaticity are interactive. The change of position of the particle over three revolutions is defined as the spiral step. The phase space of beam is distorted to a triangle and the amplitude increases spirally when the RSEX operates. The triangles will be shifted according to their momenta and the separatrices of different momenta are not superimposed when EES is placed in dispersion arc, thus the particles move outwards along different trajectories and therefore reach EES with different angles. The angle spread increases the beam loss at extraction point (EP). The beam loss is a critical issue in the period of extraction because it may lead to heat and decrease the lifetime of ESS. For EP placed in dispersion section, the extraction separatrices of different momenta are configured and the beam loss can be optimized while Hardt condition is fulfilled [7]. To study the beam loss of 3rd slow extraction, three extraction layouts of the typical lattice are designed and the beam loss is studied.

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RESONANCE AND CHROMATICITY TERM DRIVEN BY SEXTUPOLE

Sextupoles are used to resonance excitation and chromaticity correction and the layout of extraction is typically shown in Fig. 1. A pair of RSEXs (Sex 1 and Sex 3) is usually planned symmetrically to slow extraction and a pair of chromaticity sextupoles (Sex 2 and Sex 4) at symmetrically opposed position is generally configured for all momenta to fulfill Hardt condition.

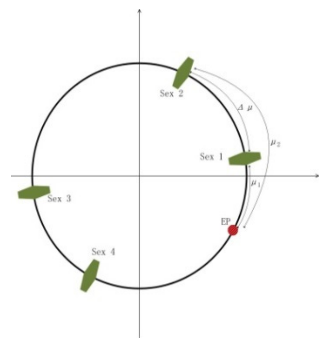

Figure 1: The generally layout of sextupoles and EP in synchrotron.

Assumed no couple, an equivalent virtual sextupole can be found by evaluating the above driving term S and chromatic term ξ' in horizontal plane as

$$\begin{aligned} S &= S_1\cos(3\mu_1)+S_2\cos(3\mu_2)+S_3\cos(3\mu_3)+S_4\cos(3\mu_4), \\ \xi' &= \frac{l_s}{4\pi}[k_1\beta_1 D_{x1}+k_2\beta_2 D_{x2}+k_3\beta_3 D_{x3}+k_4\beta_4 D_{x4}]. \end{aligned} \tag{1}$$

where, k_i is intensity of the i^{th} sextupole and the phase advance from the i^{th} sextupole to EP is μ_i, l_s denotes the effective length of sextupoles. β_i and D_{xi} are betatron function and dispersion function at the i^{th} sextupole. The normalized sextupole strength S_i

$$S_i = \frac{1}{2}\beta_i^{3/2} l_s k_i. \tag{2}$$

The maximum spiral step Δx is

$$\Delta x = \frac{3}{4} S \frac{1}{\cos\varphi} X_{EES}^2, \tag{3}$$

with the position of EES, XEES, and the angle between the separatrix and horizontal axis φ.

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Consider the horizontal betatron tune of a third - integer, i.e. $\nu_x = n \pm 1/3$, where n is integer. Twiss parameter as

$$\begin{aligned} &\mu_3 = \mu_1 \pm \frac{\pi}{3}, && \mu_4 = \mu_2 \pm \frac{\pi}{3}; \\ &\beta_1 = \beta_3, && \beta_2 = \beta_4; \\ &D_{x1} = D_{x3}, && D_{x2} = D_{x4}. \end{aligned} \tag{4}$$

So Eq. (1) is simplified as

$$\begin{aligned} &S = (S_1 - S_3)\cos(3\mu_1) + (S_2 - S_4)\cos(3\mu_2), \\ &\xi' = \frac{l_s}{4\pi}[(k_1 + k_3)\beta_1 D_{x1} + (k_2 + k_4)\beta_2 D_{x2}]. \end{aligned} \tag{5}$$

In fact, the tune is close to a third-integer with a tune distance $\Delta\nu$, i.e. $\nu_x = n \pm 1/3 + \Delta\nu$, so the phase advance between two sextupoles is

$$\mu_3 = \mu_1 \pm \frac{\pi}{3} + \pi\Delta\nu, \qquad \mu_4 = \mu_2 \pm \frac{\pi}{3} + \pi\Delta\nu. \tag{6}$$

and the first equation of Eq. (1) is modified as

$$\begin{aligned} S = {} & (S_1 - S_3)\cos(3\mu_1) + \frac{\Theta^2}{8} S_3 \cos(3\mu_1) + (S_2 - S_4)\cos(3\mu_2) \\ & + \frac{\Theta^2}{8} S_4 \cos(3\mu_2) + \frac{\Theta}{2} S_3 \sin(3\mu_1) + \frac{\Theta}{2} S_4 \sin(3\mu_2). \end{aligned} \tag{7}$$

with modified tune distance $\Theta = 6\pi\Delta\nu$.

For the extraction layout of EP and RSEX both located in dispersion region and the sextupole intensity of $S_1 = -S_3$, $S_2 = S_4$, so S is approximated as

$$S = 2S_1\left(1 + \frac{\Theta^2}{32}\right)\cos(3\mu_1 + \theta) + \frac{\Theta}{2} S_2\left(1 + \frac{\Theta^2}{32}\right)\sin(3\mu_1 + 3\Delta\mu + \theta), \tag{8}$$

with $\Delta\mu = \mu_2 - \mu_1$, and angle shift $\theta = \arctan(\Theta/4)$.

For typical case with extraction tune of 1.67, the angle shift is about 0.9 degrees. $\Theta^2/32$ is much smaller than one in Eq. (8), so it can be further approximated as

$$S = 2S_1\cos(3\mu_1 + \theta) + \Theta/2\, S_2 \sin(3\mu_1 + 3\Delta\mu + \theta). \tag{9}$$

For the extraction layout of EP located in dispersion section and only one RESX placed in dispersion-free area with intensity of $2S_1$. The resonance is approximately expressed as

$$S = 2S_1\cos(3\mu_1) + \Theta/2\, S_2 \sin(3\mu_1 + 3\Delta\mu + \theta). \tag{10}$$

For the extraction layout of EP and one RSEX with intensity of $2S_1$ both placed in dispersion-free straight section, the chromaticity sextupole is not needed. The resonance term is clear as

$$S = 2S_1\cos(3\mu_1). \tag{11}$$

THREE CASES EXTRACTION LAYOUTS

A compact 300 MeV synchrotron is designed and its layout is shown in the Fig. 2. The lattice of the synchrotron adopts the FODO cell based 2-fold structure, which consists of 8 dipoles and 12 quadrupoles powered by 4 families of power supply. The ring comprises two equal 180 ° arcs joined by two equal dispersion-free straight sections of 4 m respectively. The parameter of the synchrotron is listed in Table 1. The regular dipole magnet of 1.8 m length is used. The plot *d* in the figure shows the twiss parameters of the synchrotron. Injection Magnetic Septum (IMS), Electrostatic Infector (IEI) and two bump magnets are used for injection. The advantage of the design is the long dispersion-free straight section for extraction.

To study the beam loss at EP, three cases of extraction layout are designed. The RSEXs and EP are not placed in dispersion-free straight section in the plot *a* (Case 1). The EP is located in dispersion-free section and the RSEX is placed in dispersion arc in the plot *b* (Case 2). In the figure *c*, the EP and RSEX are both placed in dispersion-free straight section (Case 3). The phase advances of three cases between Sex 1 and EES are 38 °, 218 ° and 34 °, respectively. The phase advances from EES to EMS are a comfortable 41 °, which can provide 66 % kick of that of 90 ° phase advance. For Case 2 and Case 3, only one RSEX (Sex 1) is used but two sextupoles are designed for comparison. Chromaticity sextupoles, Sex 2 and Sex 4, are also considered in Case 3 through the chromaticity do not need to correct.

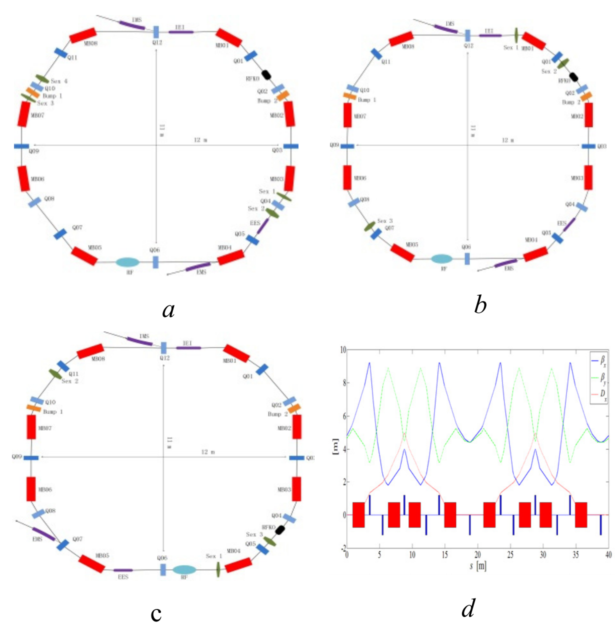

Figure 2: The three cases of extraction layout.

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Table 1: The Synchrotron Main Parameters

Parameters	**Units**	**Values**
Circumference	m	40
Ext. Energy	MeV	300
Transition γ		1.9
Tune (H/V)		1.71/1.24
Natural Chromaticity (H/V)		-0.47/-1.68
Repetition Rate	Hz	0.5
Acceptance (H/V)	π.mm.mrad	200/50
Ext. emittance	π.mm.mrad	16
Ext. Momentum Deviation	%	0.1
Accumulated Number		$2*10^{11}$

BEAM LOSS OF THREE CASES

The beam loss of extraction is also studied according to the tracking code [8]. The accelerated beam is tracked several kilo turns, even more. Particles are judged when they pass through EP with reasonable intensity of the sextupole and RFKO. Some particles hit at EES and lose, some particles enter in EES and are extracted, even some lose in pipe, but many particles per turn pass through EP and ramp again. Particles are also checked at EMS and injection region.

The beam loss of three layouts is studied based on the tracking code. The position of EES changes for three extraction layouts with same acceptance, and the intensities of RSEX are different with same spiral step. The strength of RFKO is reasonable for smooth spill. The beam loss for three cases is compared without chromaticity correction in Table 2. It is easy to see that the beam loss with same spiral step is different in three cases. The beam loss is biggest of Case 1 and it is smallest of Case 3, which means EP and RSEX placed in dispersion-free region is useful to decrease beam loss, so the lattice with long dispersion-free straight section is predominant.

Table 2: The Ratio of Beam Loss at EP for Three Layouts

Spiral step/mm	**Case 1 /%**	**Case 2 /%**	**Case 3 /%**
8.0	3	2.9	2.8
4.5	4.7	4.3	4
3.0	6.8	7	6.2
2.0	11.5	12.5	10

To the same spiral step in Case 1 and Case 2, the dispersion function is corrected to fulfill Hardt condition, and the beam loss ratio reduces about 2 %, so it is visible to restrict beam loss for fulfilling Hardt condition.

For the same spiral step, two RSEXs with anti-equal intensity in Case 1 is used in the simulation, and the beam loss at EP is same with only Sex 1 used, but some particles lose at IMS and EMS, which means that the aperture of vacuum components should be larger. Therefore, the layout of one RSEX in Case 3 is advantage.

SUMMARY

The beam is continuous extracted by using the sextupole. The spiral step with different sextupoles in the synchrotron is theoretically calculated and it is consistent with simulation result. Three typical layouts of extraction are considered to track study the beam loss and Hardt condition. It is advantage to beam loss for the extraction of EP and RSEX both placed in dispersion-free straight section. The beam loss can further decrease when Hardt condition is fulfilled.

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