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Some Studies on Increasing the Luminosity of BEPCⅡ *

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Abstract BEPCⅡ, the upgrading project of the Beijing Electron-Positron Collider (BEPC), has been designed with a luminosity of $10^{33}\text{cm}^{-2}\cdot\text{s}^{-1}$ at the τ-charm energy region. According to the beam-beam simulation results, the luminosity of BEPCⅡ with a crossing collision angle of 11mrad is about $0.50\times10^{33}\text{cm}^{-2}\cdot\text{s}^{-1}$ with the original operation mode at the working point of 6.53/5.58. To increase the operating luminosity of the BEPCⅡ, a low momentum compaction factor (α_{P}) collision mode has been studied which can increase the luminosity to $0.54\times10^{33}\text{cm}^{-2}\cdot\text{s}^{-1}$. If the bunch length of the low α_{P} mode is reduced from 1.5cm to 1.2cm, a mode with vertical beta function at IP equal to 1.2cm could push the luminosity to $0.828\times10^{33}\text{cm}^{-2}\cdot\text{s}^{-1}$ at the working points 6.53/5.56.

Key words BEPCⅡ, luminosity, lattice, dynamic aperture, working point

1 Introduction

BEPCⅡ is an upgrading project of the Beijing Electron-Positron Collider (BEPC), where a new inner ring will be installed inside the old one. The double-ring geometric structure of the BEPCⅡ makes each ring not to be a 4-folder symmetrical structure, though a symmetry still exists between the electron and positron rings. Based on several design criteria, a geometric design which satisfies both collision and synchrotron radiation modes requirements is done[1].

From Eq. (1), one can calculate the head-on collison luminosity

$$L(\text{cm}^{-2}\cdot\text{s}^{-1}) = 2.17\times10^{34}(1+R)\xi_y\frac{E(\text{GeV})k_{\text{b}}I_{\text{b}}(\text{A})}{\beta_y^*(\text{cm})}, \quad (1)$$

where $R=\sigma_y^*/\sigma_x^*$ is the beam aspect ratio at the interaction point (IP), ξ_y the vertical beam-beam parameter, E the beam energy, β_y^* the vertical envelope function at IP, k_{b} the bunch number in each beam and I_{b} the bunch current.

The beam-beam interaction simulation was carried out with several computer codes, which shows a luminosity reduction in different degrees compared with the designed luminosity. The results from one of the codes show that the luminosity of BEPCⅡ with a crossing collision angle of 11mrad is about $0.50\times10^{33}\text{cm}^{-2}\cdot\text{s}^{-1}$ with the original operation mode at the working point of 6.53/5.58[2]. To increase the luminosity of BEPCⅡ, in this paper we will discuss how to adjust the lattice to reach high luminosity. First, the BEPCⅡ lattice is adjusted to reduce the momentum compaction factor α_{P} while keeping the vertical beta function at 1.5cm[3]. The corresponding luminosity can be increased to $0.54\times10^{33}\text{cm}^{-2}\cdot\text{s}^{-1}$. The parameters of the design mode (normal mode) and the low α_{P} mode (low alpha mode) are listed in Table 1.

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Table 1. Main parameters of BEPCⅡ.

parameter	normal mode	low α_P mode
energy E/GeV	1.89	1.89
natural chromaticity x/y	$-11/-21$	$-12.3/-19.8$
tune x/y	6.53/5.58	6.53/5.58
emittance x/(nm·rad)	144	150
momentum compaction factor	0.0235	0.0188
bunch length/cm	1.5	1.2
beta-function at IP(x/y)/m	1/0.015	1/0.015
luminosity/(cm^{-2}·s^{-1})	0.5×10^{33}	0.56×10^{33}

The threshold of microwave instability can be estimated according to the Boussard or Keil-schnell criteria[4]:

$$I_{\rm th}=\frac{\sqrt{2\pi}\alpha_{\rm P}\dfrac{E}{e}\sigma_{\rm e0}^2\sigma_{\rm l0}}{R\left|\dfrac{Z}{n}\right|_{\rm eff}}. \qquad (2)$$

For low alpha mode, $\alpha_{\rm P}$=0.0188, $\sigma_{\rm l0}$=1.08cm, other parameter is the same as the original mode[1], it can be calculated from Eq. (2) that the threshold of microwave instability will be 34mA which is much larger than the BEPCⅡ single bunch current 9.8mA.

Secondly, the quadrupoles in the ring are adjusted to give the vertical beta function equaling to 1.2cm at IP, with the working point kept at 6.53/5.58, Finally, with the vertical beta function being 1.2cm at IP, the working point is moved to 6.53/5.56. At the same time, maintaining a low horizontal emittance is very important for gaining a high luminosity. For a given machine, according to Eq. (3), the beta functions and the horizontal dispersion function have been adjusted to get a low horizontal emittance in the matching process.

$$\varepsilon_{x0}\propto\left\langle\gamma D_x^2+2\alpha D_xD_x'+\beta D_x'^2\right\rangle, \qquad (3)$$

where ε_{x0} is the horizontal emittance, α, β, γ are the Twiss parameters, and D_x is the horizontal dispersion function.

In the following sections, the matching procedure for these three low $\alpha_{\rm P}$ modes, the chromaticity correction, the dynamic aperture tracking results, the FMA analysis results, and the corresponding luminosity estimation with different bunch lengthening regimes are presented.

2 Mode 1: β_y^*=1.5cm@6.53/5.56

2.1 Linear lattice

As the vertical beta function at IP is kept at 1.5cm, the strength of the superconduting quadrupole SSCQ, R3OQ1 and R4IQ1 is not changed. All the other quadrupoles are matched to move the working point to 6.53/5.56.

At the same time, the following criteria are abided by: the horizontal phase advance between the two kickers in the outer ring should be π strictly; the dispersion should be 0 in the RF and injection regions; the emittance should be kept as low as possible; and the natural chromaticity should be as large as possible.

Using MAD[5], a linear lattice that fulfills the above requirements is obtained, whose twiss parameters are shown in Fig. 1.

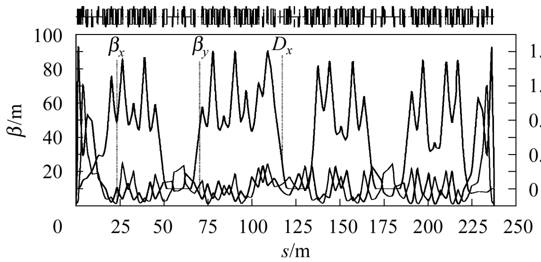

Fig. 1. BEPCⅡ ring twiss parameters.

2.2 Chromaticity correction and DA

Nine sextupoles in each arc region are used to correct the first order chromaticity from negative values to 1 and the second order chromaticity bigger than 15. The third order chromaticity is also controlled. They are divided into 5 families of defocusing sextupoles (SD) and 4 families of focusing sextupoles (SF). The families of sextuples are set as SD1, SF1, SD2, SF2, SD3, SF3, SD4, SF4, and SD5 from the IP to the injection region in the southern half ring and from the injection region to the RF region in the northern half ring.

The tune variation and beta function variation at IP versus momentum deviation up to ±0.6% is shown in Fig. 2.

Tracking for 1024 turns with 10 seeds using SAD[6], the dynamic aperture with all magnets errors is obtained, as shown in Fig. 3.

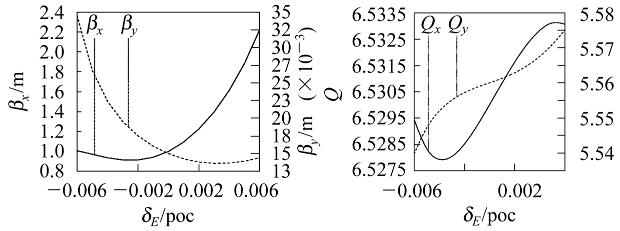

Fig. 2.　Beta and tunes vs $\delta p/p$.

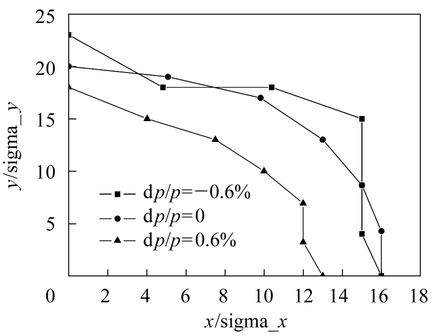

Fig. 3.　Dynamic aperture with all errors.

3　Mode 2: $\beta_y^*=1.2$cm@6.53/5.58

3.1　Linear lattice

As the vertical beta function at IP should be decreased to 1.2cm, the strength of the quadrupole in the mini-beta insertion should be increased. Here the k1 value of R3OQ1A is kept the same as the original value 1 and the k1 value of R3OQ1B is adjusted from 0.7232 to 0.73. The quadrupoles in region 3 and 4 are adjusted to satisfy other criteria which are similar to the criteria in mode 1. The quadrupoles in region 1 and 2 is not changed. In that way the phase advance between kickers and the beta function at the RF cavity are not changed.

The twiss parameters in region 3 and 4 are shown in Fig. 4.

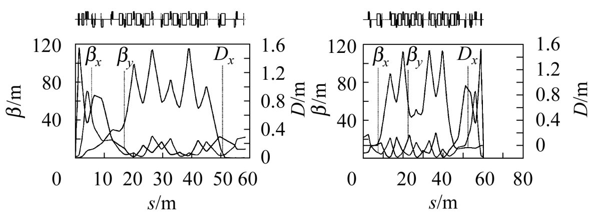

Fig. 4.　Twiss parameters in R3O and R4I.

3.2　Chromaticity correction and DA

The arrangement of the sextupoles is the same as in mode 1. The first order chromaticity is corrected from negative values to 1 and the second order chromaticity bigger than 10.

The tune variation and beta function variation at IP versus momentum deviation up to ±0.6% is shown in Fig. 5(a). Tracking for 1024 turns with 10 seeds using SAD[6], the dynamic aperture with all magnets errors is shown in Fig. 5(b).

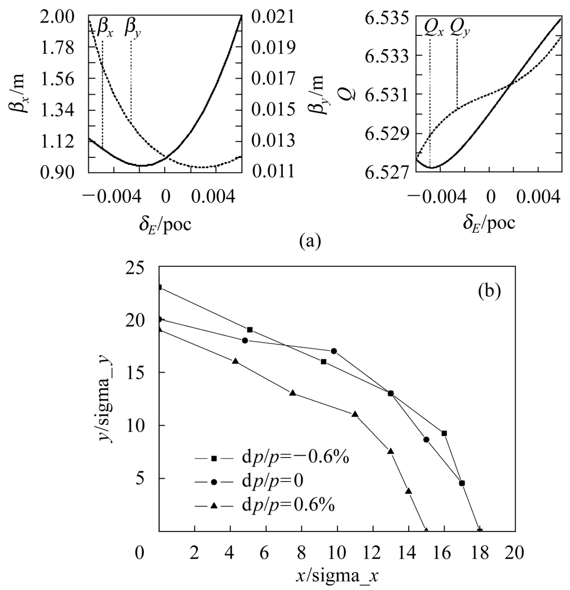

Fig. 5.　(a) Beta and tunes vs $\delta p/p$; (b) mean dynamic aperture with all errors.

4　Mode 3: $\beta_y^*=1.2$cm@6.53/5.56

4.1　Linear lattice

The quadrupoles in the whole ring are adjusted to move the working point to 6.53/5.56 while all the criteria are satisfied. The twiss parameters of the ring are shown in Fig. 6.

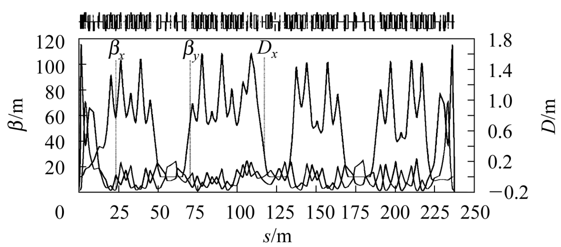

Fig. 6.　BEPCⅡ ring twiss parameters.

4.2 Chromaticity correction and DA

The arrangement of the sextupoles is the same as in mode 1. The first order chromaticity is corrected from negative values to 1 and the second order chromaticity bigger than 10.

The tune variation and beta function variation at IP versus momentum deviation up to ±0.6% are shown in Fig. 7(a). Tracking for 1024 turns with 10 seeds using SAD[6], the dynamic aperture with all magnets errors is shown in Fig. 7(b).

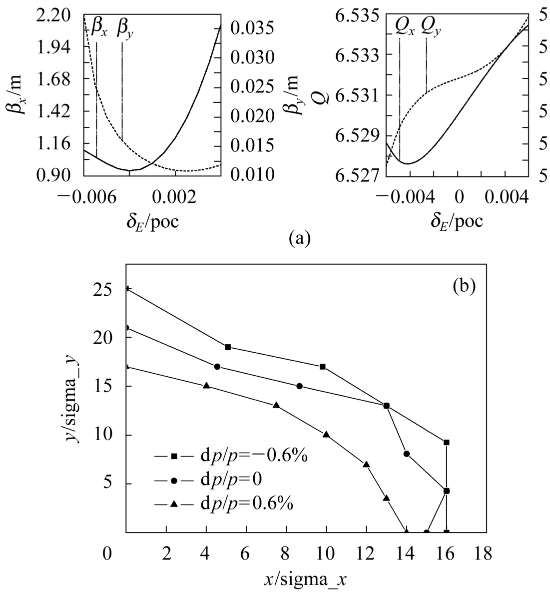

Fig. 7. (a) Beta and tunes vs $\delta p/p$; (b) mean dynamic aperture with all errors.

5 Frequency analysis

To select a good working point which is far away from the critical resonance lines, FMA is used to optimize the dynamic aperture[7]. After optimization, the FMA result of the original low alpha mode is shown in Fig. 8[2], where 3600 particles are tracked for 1024 turns to do the frequency map analysis.

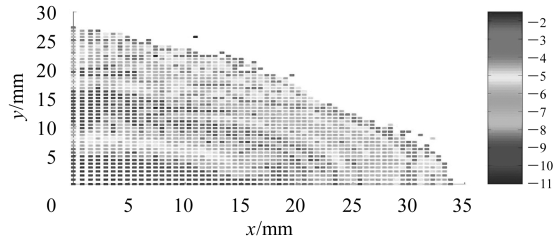

Fig. 8. FMA analysis result.

From the frequency map result, it can be seen that the nonlinear resonance line is not very obvious in this condition and the result is relatively good.

6 Comparisons of luminosities

It is very important to make luminosity estimation on the bunch length. In this paper, we will use two bunch length estimation methods used in Ref. [1] and Ref. [8]. The natural bunch length of the BEPCⅡ low alpha and BEPCⅡ normal mode mode is 1.08cm and 1.3cm respectively. According to the method established in Ref. [1], the bunch length will be increased to 1.2cm and 1.5cm at the designed bunch current, respectively. According to the method established in Ref. [8], the corresponding increased bunch length is 1.8cm and 2.0cm at the designed bunch current, respectively[8, 9]. To estimate the luminosity, we use Zhang's beam-beam simulation program[10]. In Table 2, with the bunch of 1.2cm and 1.5cm, we present the working point and corresponding luminosities. As for the bunch length of 1.8cm and 2cm, the corresponding luminosities are given in Table 3.

Table 2. Main parameters of these modes.

parameter	normal mode	mode 1	mode 2	mode 3
energy E/GeV	1.89	1.89	1.89	1.89
natural chromaticity x/y	$-11/-21$	$-12/-21$	$-11/-25$	$-11/-25$
tune x/y	6.53/5.58	6.53/5.56	6.53/5.58	6.53/5.56
emittance x/(nm·rad)	144	144	141	142
momentum compaction factor	0.0235	0.0187	0.0189	0.0189
bunch length/cm	1.5	1.2	1.2	1.2
beta-function at IP(x/y)/m	1/0.015	1/0.015	1/0.012	1/0.012
luminosity/(cm^{-2}·s^{-1})	0.5×10^{33}	0.77×10^{33}	0.637×10^{33}	0.828×10^{33}

Table 3. Luminosity with another bunch lengthening regime.

	bunch length/cm	luminosity/($cm^{-2}\cdot s^{-1}$)
normal mode	2.0	0.482×10^{33}
mode 1	1.8	0.569×10^{33}
mode 2	1.8	0.507×10^{33}
mode 3	1.8	0.613×10^{33}

Since the beam-beam effect and the luminosity depend on working point, if one can move the working point more close to the upper side of half integer, theoretically speaking[11], one can have higher luminosity than the luminosity results presented in this paper.

7 Conclusions

Three low α_p collision modes for BEPCⅡ have been developed. The aim is to increase the luminosity by reducing the vertical beta function at IP from 1.5cm to 1.2cm and to move the working point to high luminosity region. The dynamic aperture is acceptable for collision but still a little small for injection. So the BEPCⅡ ring can be tuned to these modes after the beam has been injected into the ring. For the natural bunch length of 1.08cm and the vertical beta function of 1.2cm, the highest luminosity reached is $0.828\times10^{33}cm^{-2}\cdot s^{-1}$ at the working point 6.53/5.56 with the assumption that the bunch length can reach 1.2cm. Higher luminosity possibility is understudy.

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为提高BEPCⅡ亮度进行的一些研究*

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摘要 BEPCⅡ是BEPC的升级工程, 它被设计工作在亮度为$1\times10^{33}cm^{-2}\cdot s^{-1}$的τ-charm能区. 根据用几个不同的程序进行的束–束相互作用的模拟结果, BEPCⅡ的亮度较设计亮度有不同程度的下降. 其中一个程序的计算结果表明, 在原设计对撞模式下运行, BEPCⅡ的运行亮度只能达到$0.50\times10^{33}cm^{-2}\cdot s^{-1}$. 为了提高BEPCⅡ的运行亮度, 研究了小动量压缩因子的对撞模式, 亮度可以提高到$0.54\times10^{33}cm^{-2}\cdot s^{-1}$. 相应的束长由1.5cm减小到1.2cm. 为了和1.2cm的束长相匹配, 又研究了对撞点垂直β函数等于1.2cm的对撞模式. 根据束–束相互作用的模拟结果, 选择了几个高亮度的工作点, 对它们的线性lattice和动力学孔径等进行了研究和优化. 其中, 最高的亮度可以达到$0.828\times10^{33}cm^{-2}\cdot s^{-1}$.

关键词 BEPCⅡ 亮度 磁聚焦结构 动力学孔径 工作点

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