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Optimization Studies on BEPC Ⅱ Future Pre-injector with Two SHBs

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Abstract The BEPC Ⅱ future pre-injector consists of a thermionic gun followed by two subharmonic bunchers (SHB), a travelling wave prebuncher and a travelling wave buncher. All components downstream of the gun are immersed in a solenoid field for transverse focusing. Beam dynamics simulation and optimization have been carried out with programs PARMELA and EGUN. SHBs' bunching voltage and bunching drift distance, prebuncher and buncher's phase and acceleration gradient, and solenoid field profile have been studied. The bunch charge limitation for 10ps bunch length at the buncher exit is also investigated.

Key words pre-injector, beam dynamics, subharmonic buncher

1 Introduction

In order to further increase the injection rate of positron beam from the linac to the storage ring of BEPC Ⅱ (Beijing Electron Positron Collider Upgrade project), the pre-injector is planned to have the capability of providing a low emittance and high intensity single bunch electron beam for the positron beam production. For this purpose, the primary electron bunch needs to have more than 9nC charge, and the bunch length at the buncher exit needs to be limited as short as 10ps to meet the longitudinal acceptance of downstream RF accelerating structures[1]. In addition, a narrow energy spread and a small emittance of the primary electron beam are expected to have a high positron production rate[2—4].

Furthermore, BEPC Ⅱ will adopt the two-bunch generation and acceleration scheme to double the positron injection rate to the storage ring in the future[1], so it is very important to have a new pre-injector with good bunching characteristics .

To meet these requirements, BEPC Ⅱ future pre-injector has been designed and optimized by introducing two subharmonic bunchers[5]. With this new pre-injector, an initial 1.5ns electron bunch at the gun exit can be bunched to 10ps at the buncher exit, with bunch charge of more than 9nC. In this paper, the frequency selection scheme of BEPC Ⅱ future pre-injector is described first, and then the studies on optimization of the pre-injector are presented. In addition, the bunch charge limitation at the buncher exit is also described.

2 Frequency selection scheme of the BEPC Ⅱ future pre-injector

To ensure a precise injection timing and make the injection flexible, the subharmonic buncher (SHB) frequencies as well as the linac frequency (2856MHz) must be phase-locked to the ring frequency. To do this, each of the four frequencies, i.e., the ring frequency $f(\mathrm{r})$, the linac frequency $f(\mathrm{l})$, the first subharmonic frequency $f(\mathrm{s1})$, and the second subharmonic frequency $f(\mathrm{s2})$, must be a multiple of a common subharmonic frequency $f(\mathrm{sub})$.

Table 1. Various frequency relations.

	Multiple	Frequency/MHz	Period/ns
Common Frequency	1	17.85	56.02
SHB1	8	142.80	7.000
SHB2	4×8	571.20	1.751
Linac	5×4×8	2856.00	0.350
Ring	4×7	499.80	2.001

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The ring frequency of 499.8MHz has been fixed, which is 7/40 of 2856MHz, so the common frequency of 17.85MHz can be selected. Because 17.85MHz is 1/80 of 2856MHz, the SHB1's frequency can be chosen as 17.85MHz × 8 = 142.8MHz, and the SHB2's frequency can be 17.85MHz × 32 = 571.2MHz. The frequency relations between the linac and the ring are listed in Table 1.

3 Simulation and optimization of BEPCⅡ future pre-injector

3.1 Optimized layout of the pre-injector

By a great deal of beam dynamics calculations with the program PARMELA[6], we have proposed the optimized layout of the BEPCⅡ future pre-injector, as shown in Fig.1. The pre-injector consists of a thermionic electron gun, a 142.8MHz SHB, a 571.2MHz SHB, a 4-cell traveling wave prebuncher and a 35-cell traveling wave buncher. Both of the 2 SHBs are reentrant cavities.

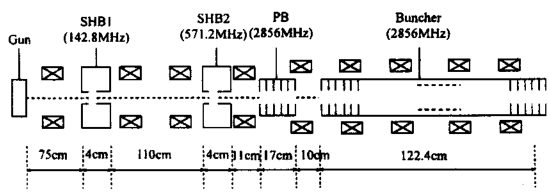

Fig.1. Schematic layout of the components for the BEPC Ⅱ pre-injector with 2 SHBs.

3.2 Electron gun

The electron gun is a conventional thermionic triode gun with the cathode-grid assembly Y796 (EIMAC). Because high gun voltage can suppress the space charge effect, and low gun voltage can simplify the process of bunching, the gun voltage of 150kV has been chosen at moderate level. When the gun works with narrow pulses, the emission current can be up to higher than 12A, the normalized emittances at the gun exit are 20—25πmm·mrad for emission currents from 6A to 12A. The gun's geometry has been simulated and optimized[1] by code EGUN[7] to minimize the emittance for a 10A bunch current. Fig.2 shows the beam optics of the electron gun with a bunch current of 10A and a normalized emittance of 20.34πmm·mrad at the gun exit.

A bunch length of 1.5 ns at the gun exit was chosen

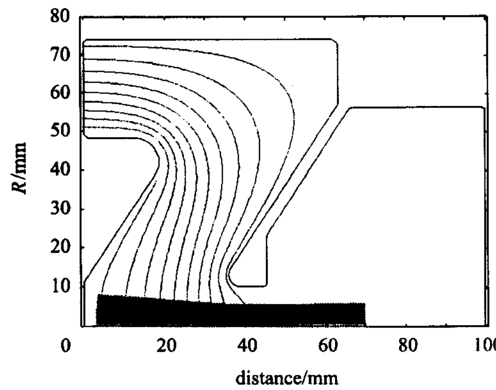

Fig.2. Beam optics of the electron gun.

by following reasons: a) this bunch length at the gun exit needs to be chosen as long as possible in order to suppress the space charge effect; b) in order to have a clean capture by SHB1, this bunch length at the gun exit needs to be less than a quarter of SHB1's period time.

3.3 Guidelines on simulation and optimization

Starting with the transverse beam parameters at the gun exit calculated with EGUN, a 10nC/150kV and 1.5 ns electron bunch is used as an input of PARMELA simulations in order to optimize the process of bunching and to have the optimized layout of the pre-injector. At the buncher exit the energy of the particles is about 16—20MeV, the normalized rms bunch emittance is expected to be less than 20πmm·mrad[1], with more than 90% of the initial particles in the phase spread of 10° at 2856MHz. So the bunch length at the buncher exit is required to be about 10ps with the bunch charge of more than 9nC.

The first subharmonic buncher (SHB1) is located at a distance of 75cm downstream from the gun. This distance is needed to install some equipment, such as the beam monitors to check the beam current, size, emittance and the beam position at the gun exit, the solenoid lens and other focusing lens to focus and match the beam into SHB1, and a vacuum valve and vacuum pumps.

To have the best bunching results, the following guidelines have been applied in the optimization process:

a) At the entrance of SHB2, more than 95% of the initial particles need to be found in 120° of 571.2MHz;

b) At the entrance of prebuncher, the bunch length is expected to be about 0.18ns, which is approximately equivalent to about 180° of 2856MHz;

c) The bunch current at SHB2 is greater than that at SHB1, so SHB2's modulation voltage is required a little higher than that of SHB1;

d) In order to suppress the emittance growth caused by energy spread, SHBs' voltages need to be as low as possible, but the voltages must be not too low due to the space charge effect;

e) The distance between prebuncher (PB) and buncher (B) is preferred as short as possible for evading any de-bunching effects[8];

f) In order to control the beam size and minimize the emittance growth due to space charge effects, all components of the pre-injector need to be immersed in a solenoid-focusing field. Especially at prebuncher and buncher, the strength of solenoid field must be increased rapidly;

g) Raising the SHBs' voltage can minimize the subsequent drift space[8], but the emittance growth caused by the high energy spread will be large;

h) High PB acceleration gradient is bad for bunching, but low PB acceleration gradient is bad for suppressing the space charge effect, so the PB acceleration gradient needs to be optimized carefully;

i) The buncher acceleration gradient is expected as high as possible for suppressing the space charge effect and completing the bunching process rapidly.

Followed the above criteria the optimized bunching system has been found, as shown in Fig.1.

3.4 Selection of the principle components' phase

If the reference particle in the middle of the electron bunch reaches the SHBs at the zero phases of SHBs, then the velocity differences between the head particles and the reference particle will be smaller than the velocity differences between the tail particles and the reference particle. This effect will cause the beam emittance growth due to the longitudinal asymmetry of the particle distribution. Therefore, in order to decrease the emittance growth and keep the longitudinal symmetry of the bunch, the reference particle must be not on the zero phases of SHBs when the bunch is modulated by SHBs. For the optimization of the BEPCⅡ future pre-injector, the reference particle is put on the decelerating phase of SHB1 and on the accelerating phase of SHB2. It was found that if the reference particle's energy decreases 20keV to 130keV in SHB1 and then increases 20keV to 150keV in SHB2, the best bunching result can be obtained.

The prebuncher of the pre-injector is a 4cell, $\beta = 0.75$, $2\pi/3$-mode S-band traveling wave structure. In this kind of structure, there must be a relation between the input phase and the output phase of the particle[9], so the single particle motion in the prebuncher was studied first. Fig.3 shows the relation between the input and output phases of a single particle motion at an acceleration gradient of around 6.32MV/m in the prebuncher. The shape of the curve may vary a little when the acceleration gradient is different from 6.32MV/m, but they are alike. By this figure, the injection phase of the reference particle at the prebuncher can be chosen at the bending point of the curve if the reference particle is at the mid-bunch. Otherwise, the phase needs to be adjusted according to the differences between the reference particle and the particles at the mid-bunch.

The buncher is a 35-cell, $\beta = 1$, $2\pi/3$-mode S-band traveling wave structure. The injection phase of the reference particle at the buncher can also be chosen in the same way as that at the prebuncher.

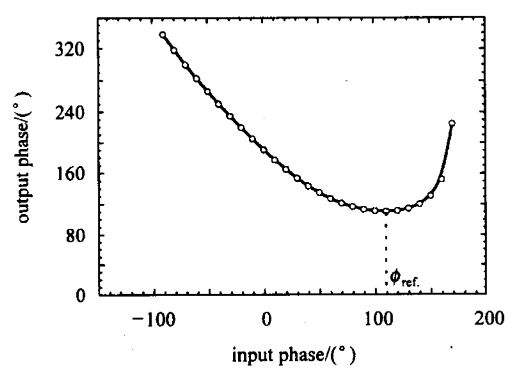

Fig.3. Relation between the input phase and the output phase of the prebuncher.

3.5 Transverse beam dynamics

In dealing with the optimization of transverse beam dynamics, two key points need to be considered. One is the capture efficiency at the buncher exit, another is the emittance variation along the whole pre-injector. If the strength of the solenoid field is higher than 0.138T, the capture efficiency at the buncher exit will be lower than 90%. On the other hand, if this strength is smaller than 0.105T, the emittance at the buncher exit will exceed

20πmm·mrad. So the strength of the solenoid field is usually larger than 0.105T and smaller than 0.138T, and the optimal value is 0.130T, as shown in Fig.4. The profile of the solenoid field can affect the emittance variation along the whole pre-injector, so this also needs to be optimized to minimize the variation. In a word, the profile and the strength of the solenoid field need to be optimized carefully[10]. Fig.4 shows the solenoid field and emittance variation along the whole pre-injector, in which all the parameters of the principle components are optimized.

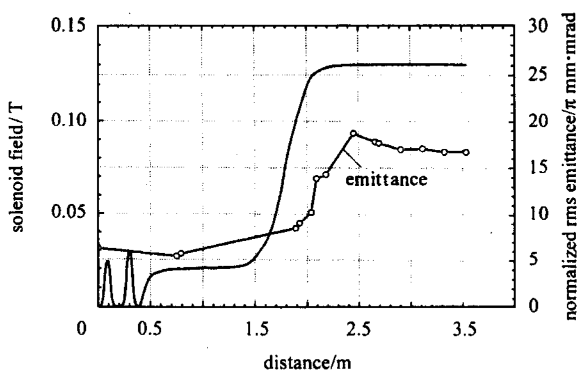

Fig.4. Solenoid field and emittance variation along the whole pre-injector.

3.6 Results of simulation and optimization

Through many simulations and optimizations on the pre-injector, if the 150kV/10nC electrons within a pulse length of 1.5ns are emitted from the gun and come into the bunching system with the parameters listed in Table 2, then at the buncher exit: a) more than 90% of the initial particles can be found in 10° of 2856MHz; b) the normalized rms emittance is 15.64πmm·mrad; c) the beam energy is 18.41 ± 1.99MeV with its rms energy spread of 4%. The ± 1.99MeV energy spread results largely from the fact that, when the bunching process is completed and the beam reaches the speed of light, it does not end up on the crest but about 40° ahead of it[11]. This energy spread is linearly correlated with the bunch length and can be removed by properly phasing the beam in the following acceleration section. In addition, there is a ± 0.49MeV uncorrelated energy spread. All of these parameters can satisfy the requirements. Fig.5 shows the simulation results with program PARMELA, indicating that the designed beam characteristics of a high intensity, single-bunched beam can be obtained using the optimized pre-injector with the parameters listed in Table 2.

Table 2. Parameters of the principle components in the pre-injector.

Parameters	SHB1	SHB2	Pre-Buncher	Buncher
Frequency/MHz	142.8	571.2	2856	2856
Bunching voltage/kV	60.84	89.96		
Gradient (E_0T)/(MV/m)			6.32	21.0

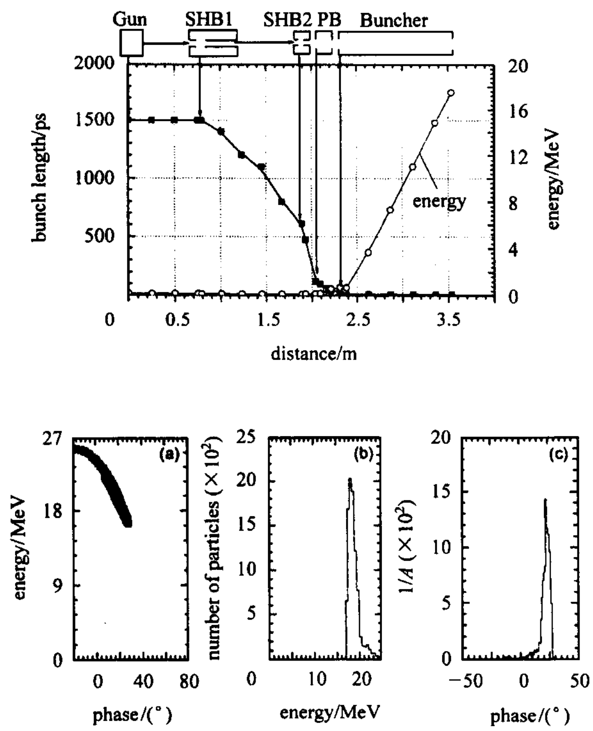

Fig.5. Simulation of the beam dynamics from the gun to the buncher exit (upper) and the beam phase space at the buncher exit (lower). (The number of initial particles in simulation is 10000.)

4 Bunch charge limitation at the buncher exit

With the optimized layout in Fig.1, bunching characteristics, such as the bunch emittance and the capture efficiency, with different input bunch charges are also studied. The results are listed in Table 3. It shows that, the larger the input bunch charge, the worse the capture efficiency, and the larger the normalized rms emittance. However, only a little more the bunch charge is within 10ps. For example, if the input bunch charge is increased to 18nC, then the normalized rms emittance is enlarged to about 20πmm·mrad, and the charge within 10ps at the buncher exit is increased only as the same as that of 16.5 nC input bunch charge. Hence, for BEPC Ⅱ

Table 3. Emittance and capture efficiency variation at the buncher exit with different bunch charges. (The bunch length at the gun exit is 1.5 ns.)

Input bunch charge/ (nC/pulse)	Capture efficiency	Charge within 10ps/nC	Normalized rms emittance/ πmm·mrad
10.0	90.01%	9.001	15.644
10.5	89.33%	9.380	15.587
12.0	88.00%	10.56	18.012
13.5	87.26%	11.78	18.315
15.0	84.71%	12.71	18.369
16.5	83.27%	13.74	18.058
18.0	76.92%	13.85	19.730

future pre-injector the charge limitation within 10ps at the buncher exit may be about 14nC and the operational charge limitation at the gun exit may be about 18 nC for the 1.5 ns beam pulse length.

Although the layout of the pre-injector was optimized to have a good bunching characteristic at a 10nC bunch, it can be also optimum for different input bunch charges by operational adjusting the parameters, such as solenoid field, to deal with the different transverse Courant-Snyder parameters caused by the different bunch charge at the gun exit. Therefore, the bunching characteristic of electron bunch with the larger input bunch charge may be preferable within the above bunch charge limitations.

5 Conclusion

Using the optimized pre-injector, more than 9 nC charge can be bunched into 10 ps of S-band, with normalized rms emittance of smaller than 20πmm·mrad. In the future, this pre-injector will be used in the two-bunch generation and acceleration scheme for BEPC Ⅱ. Up to now the physical design of SHB1 has been finished, and will be fabricated and measured in the next step.

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BEPCⅡ 未来预注入器的优化研究

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摘要　BEPCⅡ 未来的预注入器由热阴极电子枪、两个次谐波聚束器（SHB）、行波预聚束器以及行波聚束器组成．除电子枪以外，各个部分都位于螺线管磁场中．使用 PARMELA 和 EGUN 程序模拟和优化了预注入器的束流动力学．对 SHB 的聚束电压和漂移距离、预聚束器与聚束器的相位和加速梯度、螺线管磁场的形状等都进行了细致的研究和优化，并讨论了聚束器出口 10ps 束长内电荷量的极限值．

关键词　预注入器　束流动力学　次谐波聚束器

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