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Wakefield Effects on the BEPCII Injector Linac *

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Abstract The high current and short bunch of the electron beam in the BEPCII injector linac cause the wakefield effects on the beam performance dilution. These wakefield effects on longitudinal and transverse beam dynamics are systematically studied with analysis and numerical beam modeling, including the single bunch short-range wake effects and the multi-bunch long-range wake effects on beam energy, energy spread, emittance, orbit offset and primary electron beam spot size on the positron production target. The measures to effectively cure these wake effects are also studied.

Key words electron linac, wakefield effects, cure methods

1 Introduction

To meet the high luminosity requirement of the Beijing Electron Positron Collider upgrade project (BEPCII), its injector linac must provide high currents of electron and positron beams with the beam energy of 1.89GeV and with a small emittance (1.6π mm · mrad for 37mA positron beam) and a small energy spread (±0.5% for positron beam and for 200 mA electron beam) to provide a high injection rate of 50mA/min (for positron beam) into the storage ring[1]. The high current and short bunch of the electron beams in the BEPCII injector linac cause the wakefield effects on the beam performance dilution, leading to the large mismatches with the requirements of beam injection into the BEPCII storage ring. These effects both on longitudinal and transverse beam dynamics have been systematically studied by analysis and numerical beam modeling with LIAR (LInear Accelerator Research) code[2]. These studies include the single bunch short-range (SR) wake effects and multi-bunch long-range (LR) wake effects on the beam energy, energy spread, emittance, orbit offset and the beam spot size. The most important wake effect is caused by the primary electron beam, which has the pulse length of 1ns and the pulse repetition rate of 50Hz. Each beam pulse consists of three bunches in the 2856MHz RF structure and with a large bunch charge of 2.5nC. The electron beam used for injecting into the storage ring has a bunch charge of 0.35nC, whose wake effects can not be negligible either due to the long distance (~190m) travel of the bunch from pre-injector to the linac end. The positron beam has a bunch current of only 21 pC, whose wake effects can be negligible by the beam modeling. To cure the wake effects on the beam quality dilutions some measures have been studied, for instance, by optimizing the phase of the bunch on the accelerating wave to cure the bunch energy spread dilution caused by the single bunch longitudinal wake effect, by properly timing the electron beam pulse and RF pulse to cure the bunch to bunch energy variation caused by the multi-bunch longitudinal wake effect, and by controlling the accelerating structure offset and employing the beam orbit correction scheme to cure the beam emittance, beam orbit and beam spot size dilutions caused by the single-and multi-bunch transverse wake effects.

2 Longitudinal wake effect

2.1 Single bunch longitudinal wake effect

A primary electron beam used for the positron pro-

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duction comes from the electron gun with a beam pulse length of 1ns, and a pulse charge of 10nC. With the prebuncher, buncher and preaccelerator, which are operated at the same frequency as the main linac (2856MHz), the whole system has the total bunching efficiency of 75 %. The beam is bunched into three bunches. Each has the bunch charge of 2.5nC and the beam energy of 40MeV. Then these bunches are accelerated to about 250MeV by 4 accelerating structures and transversely focused by two quadrupole triplets, which focus the beam on the positron production target with a minimized beam spot size. Giving the primary electron beam energy and current, the smaller the spot size, the higher the positron production rate due to the larger cross section of the e^+e^- pair production[3]. A zero-order minimum beam spot size on the target can be easily obtained by optimizing the beam optics with two quadrupole triplets upstream the target. However, due to the low beam energy and large energy spread (usually about 5 %) caused by the bunching processes, the chromatic effect in the quadrupole magnets may cause the beam spot size dilution[4]. Again, due to the low beam energy and the large bunch charge, the longitudinal wake effect may cause an additional beam energy spread dilution, leading to an additional chromatic effect and a beam spot size dilution.

The single bunch wake effect can be well described by the two-macroparticle model[5]. The energy variation due to the single bunch longitudinal wake for head and tail macroparticles (each has the charge of $Ne/2$ and are separated by a distance d) respectively are

$$\frac{\mathrm{d}E_{\mathrm{h}}}{\mathrm{d}z} = -\frac{Ne^2}{4} W_{/\!/}(0)$$

and

$$\frac{\mathrm{d}E_{\mathrm{t}}}{\mathrm{d}z} = -\frac{Ne^2}{4} W_{/\!/}(0) - \frac{Ne^2}{2} W_{/\!/}(d).$$

For the SLAC type of BEPCII accelerating structure (2856MHz) and with a bunch length of 3mm, the calculated wake functions are $W_{/\!/}(0) = 225\mathrm{V \cdot pC^{-1} \cdot m^{-1}}$ and $W_{/\!/}(3\mathrm{mm}) = 57.4\mathrm{V \cdot pC^{-1} \cdot m^{-1}}$[2]. Hence the averaged bunch energy loss (beam loading) in the 4 accelerating structures (each 3.05m long) upstream the target is about 1.68MeV, and the energy difference between head and tail macroparticles is about 0.86MeV, leading to an additional beam energy spread of 0.34 %.

To compensate the averaged bunch energy loss, one can apply a little more RF power from the power source. While to compensate the bunch energy spread, one can put the bunch center off crest of the accelerating wave, so that the particles in the tail and head parts having higher and lower energy gain, respectively. Beam modeling with LIAR code has shown that the optimized phase to minimize the bunch energy spread for primary electron beam is $-2°$, as shown in Figure 1, and $-0.5°$ for the 1.89GeV injection electron beam with a bunch charge of 0.35nC.

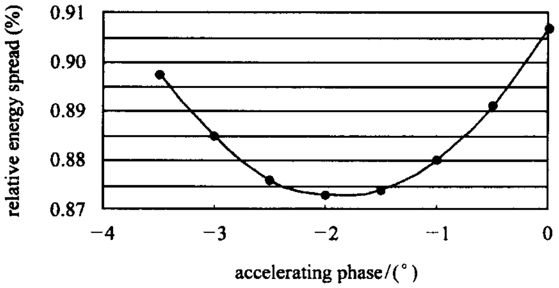

Fig.1. Bunch energy spread vs. accelerating phase.

In the beam modeling with LIAR here, each beam pulse has 3 bunches, each bunch is divided into 20 slices longitudinally within the bunch length, and each slice has 20 mono-energetic beam ellipses Gaussian distributed within the beam energy spread. The particles are Gaussian distributed longitudinally within the bunch length. The initial particles are uniformly distributed in the transverse phase space within the initial emittance. The effects on the primary electron beam spot size dilution caused by wake induced energy spread will be described in the following section of transverse wake effects.

2.2 Multi-bunch longitudinal wake effect

For multi-bunch dynamics only the fundamental accelerating mode (beam loading) is important, and for BEPCII constant gradient structure, the loaded accelerating gradient is[6]

$$\frac{\mathrm{d}E}{\mathrm{d}z} = \frac{\mathrm{d}E_0}{\mathrm{d}z} - \frac{W_{/\!/}(s)Q_{\mathrm{b}}\tau}{1-\mathrm{e}^{-2\tau}}\left(\frac{1-\mathrm{e}^{-2\tau}}{2\tau} - \mathrm{e}^{-2\tau}\right).$$

where $Q_{\mathrm{b}} = 2.5\mathrm{nC}$ is the bunch charge, $\tau = 0.57$ the attenuation of the structure, $W_{/\!/}(s)$ the wake function at a distance of s. The long-range wakefields can be specified in a simply form in the LIAR-code, in which wakefields from one bunch to the next are presented by a point-like wake kick (with unit of $\text{V}\cdot\text{pC}^{-1}\cdot\text{m}^{-1}$) plus its first derivative in position s along the bunch. For the SLAC type S-band structure and BEPCII Linac's bunch train constitution (3 bunches in 1ns beam pulse with the bunch spacing of 10.5cm), we have[2]

$$W_{/\!/}\ (10.5\text{cm}) = 53.11\text{V}\cdot\text{pC}^{-1}\cdot\text{m}^{-1}$$

and

$$W_{/\!/}\ (21\text{cm}) = 40.47\text{V}\cdot\text{pC}^{-1}\cdot\text{m}^{-1}.$$

Thus in the BEPCII Linac, the second bunch will meet a loaded gradient of 31.2kV/m caused by the 1st bunch, and the 3rd bunch will meet a totally loaded gradient of 55.0kV/m caused by the 1st and 2nd bunches. After traveling 12m of the 4 accelerating structures, the maximum bunch to bunch energy variation will be 0.66MeV, and the relative energy spread for the 250MeV primary electron bunch will be 0.26 %. The effects on the primary electron beam spot size dilution caused by wake induced energy spread will be described in the following section of transverse wake effects. To compensate the multi-bunch longitudinal wake effect, one could adjust the timing of the bunch train, letting the 1st, 2nd and 3rd bunches enter the structures at 0.70ns, 0.35ns and 0ns respectively, before the filling time of 0.83μs, so that the input RF field in the structure is ramped during the beam pulse and hence the most bunch to bunch energy variation in a short bunch may be compensated. The best timing can be defined by measuring each bunch's energy with the beam position monitor (BPM) installed at a downstream position where the dispersion is larger.

Both single bunch and multi-bunch longitudinal wake effects on the primary electron beam and on the injection (into storage ring) electron beam are listed in Table 1, in which the RF power jitter of ±0.1 % and the phasing error of ±2° have been taken into account.

Table 1. Longitudinal wake effects on the BEPCII-Linac's beam energy and energy spread.

Beams	Beam Loading (two-particle model)	Beam Loading (LIAR)	Bunch E. Spread due to SR-wake (two-particle model)	Bunch E. Spread (phase)	Bunch E. Spread (Opti. phase)	Beam E. Spread (incl. LR wake) (Opti. phase)
250 MeV e-Beam /(2.5nC/b)	−1.68MeV (−0.67%)	−1.98MeV (−0.79%)	0.86MeV (0.34%)	1.10% (0°)	0.97% (−2°)	1.13% (−2°)
1.89GeV e-Beam /(0.34nC/b)	−3.14MeV (−0.17%)	−3.71MeV (−0.20%)	1.61MeV (0.085%)	0.49% (0°)	0.47% (−0.5°)	0.50% (−0.5°)

3 Transverse wake effects

3.1 Single bunch transverse wake effects

By the two-macroparticle model, if the initial bunch offset x_0 is at $z = 0$, then at $z = s$, the tail particle's further offset caused by the wake $W_{\perp}(d)$ of head particle is[6]

$$\left[\frac{\Delta x}{x_0}\right]_{\max} = \frac{Ne^2 W_{\perp}(d)}{4kE} \times s.$$

where k is the quadrupole focusing strength, $k \propto \frac{L_q}{E}\frac{\partial B}{\partial r}$, with the quadrupole effective length L_q, magnetic gradient $\frac{\partial B}{\partial r}$ and particle energy E. For the SLAC type of BEPCII structure, if the bunch length is 3 mm, then we have $W_{\perp}(3\text{mm}) = 3.4\text{kV}\cdot\text{pC}^{-1}\cdot\text{m}^{-2}$.

To cure this effect, besids controlling the misalignment of the accelerating structures, an orbit correction scheme will be adopted in the BEPCII Linac. Table 2 shows the beam modeling results of single bunch wake effects on the primary electron beam emittance and spot size with LIAR-code. By comparing the results with and without orbit correction, one can find that the orbit correction scheme is effective[7]. While the well known BNS damping to cure the single bunch transverse wake effect could not be applied in BEPCII Linac, since the linac is not long enough.

Table 2. Single bunch transverse wake effects.

Initial beam offset/mm	Normalized emittance growth(%)		Beam spot size at target/mm	
	No Correction	Correction	No Correction	Correction
0.1	19	17	0.61	0.60
0.2	24	17	0.64	0.60
0.3	32	17	0.69	0.60
0.4	42	17	0.77	0.60
0.5	54	17	0.85	0.61
0.6	68	17	0.93	0.61
0.7	83	17	1.03	0.61
0.8	99	17	1.12	0.61
0.9	116	17	1.23	0.62
1.0	133	17	1.28	0.62

3.2 Multi-bunch transverse wake effects

As it is well known, the multi-bunch transverse wake causes the cumulative BBU (Beam Break-UP) effect. Different from the single bunch BBU, its wake function $W_{\perp}(d)$ is dominated by one or a few resonators with large shunt-impedance $r_{\perp n}$[6],

$$W_{\perp}(d) = \sum_{n} \frac{r_{\perp n}\omega_n}{Q_n} e^{-\frac{\omega_n d}{2cQ_n}} \sin\left(\frac{\omega_n d}{c}\right) .$$

Same as the long range longitudinal wake, the long range transverse wakefields from one bunch to the next can also be represented by a point-like wake kick (with the unit of $\mathrm{V \cdot pC^{-1} \cdot m^{-2}}$) plus its first derivative in the position d along the bunch. By this simplification, for the SLAC-type of BEPCII structure, one has

$$W_{\perp}(10.5\mathrm{cm}) = 2.064\mathrm{kV \cdot pC^{-1} \cdot m^{-2}}$$

and

$$W_{\perp}(21\mathrm{cm}) = 0.548\mathrm{kV \cdot pC^{-1} \cdot m^{-2}} .$$

To cure this BBU effect on the BEPCII Linac, besides controlling the misalignment of the accelerating structures, an orbit correction scheme will be adopted. Table 3 shows the beam modeling results with LIAR-code, in which the normalized beam emittance growth, the orbit offset and the beam spot size dilution caused by the initial beam offset induced long range and short range wake effects are listed. An effective orbit correction function is also shown in this table.

Table 3. Multi-bunch transverse wake effects.

Initial beam offset/mm	Nor. emittance growth(%)		Averaged Orbit Offset/mm		Beam spot size at target/mm	
	No Corr.	Corr.	No Corr.	Corr.	No Corr.	Corr.
0.1	31	18	0.17	0.05	0.72	0.62
0.2	64	19	0.35	0.09	0.91	0.63
0.3	108	21	0.52	0.14	1.13	0.65
0.4	157	23	0.74	0.18	1.35	0.66
0.5	208	26	0.87	0.23	1.59	0.69
0.6	262	30	1.05	0.28	1.83	0.71
0.7	316	34	1.22	0.32	2.08	0.74
0.8	371	38	1.40	0.37	2.33	0.77
0.9	427	43	1.57	0.41	2.59	0.80
1.0	483	49	1.75	0.46	2.84	0.83

Note that Table 2 and 3 have just shown the wake effects on the primary electron beam performances caused by the initial beam offset. The additional chromatic effects caused by the single bunch and multi-bunch longitudinal wake effects on the beam are also included in these tables. By the beam modeling[8], the transverse wake effects on the 1.89 GeV electron injection beam with a bunch current of 0.35 nC can not be negligible either due to the long distance (~ 190 m) travel of the bunch from the pre-injector to the linac end. Our further studies have shown that if we control the initial beam offset within ±0.3mm, and take into account the wake effects caused by the accelerating structure misalignment errors of 0.2mm(1σ), the dispersive and chromatic effects caused by the quadrupole and BPM misalignment errors of 0.2mm (1σ), and other jitter effects (e.g. RF power jitter of ±0.1% and phasing error of ±2°), then the final primary electron beam spot size on the positron production target will be about 1.0mm with orbit correction, and the energy spread and emittance of the 1.89GeV electron injection beam will meet its design goals of ±0.5% and 0.25π mm-mrad, respectively, with orbit correction, as described in other papers[8].

4 Summary

The high current and short bunch of the electron beam in the BEPCII injector linac cause the wakefield effects on the beam performance dilution. These effects both on the longitudinal and transverse beam dynamics are systematically studied with analysis and numerical beam modeling. These effects include the single bunch short-range wake effects and the multi-bunch long-range wake effects on the beam energy, energy spread, emittance, orbit offset and primary electron beam spot size on the positron production target.

To meet with the design goal of BEPCII injector linac's beam performances, the wake effects on the injector linac beams must be cured. Some effective measures to cure the wake effects have been studied: 1) optimizing the phase of the bunch on the accelerating wave to cure the bunch energy spread dilution caused by the single bunch longitudinal wake effect; 2) properly timing the electron beam pulse and RF pulse to cure the bunch to bunch energy variation caused by the multibunch longitudinal wake effect; 3) controlling the accelerating structure offset, e.g. 0.2mm (1σ) of alignment errors, and by employing the beam orbit correction scheme to cure the beam emittance, beam orbit and beam spot size dilutions due to the single bunch and multi-bunch transverse wake effects.

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BEPCII 直线注入器的尾场效应*

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摘要　BEPCII 直线注入器中的强流、短束团的尾场效应将损害束流的性能．用分析解和数值模拟计算的方法，系统地研究了尾场对纵向和径向束流动力学的影响，包括单束团的短程尾场和多束团的长程尾场对束流能量、能散、发射度、轨道和初级电子束在正电子产生靶上束斑尺寸的影响等．研究了有效抑制这些尾场效应的措施．

关键词　电子直线加速器　尾场效应　抑制措施

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