WAKEFIELD EFFECTS ON THE BEPCII INJECTOR LINAC

Shu-Hong Wang*, Peng-Da Gu, Wei-Bin Liu, Shi-Lun Pei, Zu-Sheng Zhou
Institute of High Energy Physics, the Chinese Academy of Sciences, Beijing, 100039, China

Abstract

The high current and short bunch of the electron beams in the BEPCII injector linac causes the wakefield effects on the beam quality dilution. These effects both on longitudinal and transverse beam dynamics are systematically studied with analysis and numerical beam modeling, including the single bunch short-range wake effects and 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. The measures to effectively cure these wake effects are also studied.

INTRODUCTION

To meet the high luminosity of BEPCII upgrade project, $3.2\sim10\times10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, its injector linac must provide high currents of electron and positron beams with beam energy of 1.89 GeV and with small emittance (1.6πmm-mrad for 37 mA positron beam) and small energy spread (±0.5% for positron beam and for 250 mA electron beam) for having an high injection rate of 50 mA/min (for positron beam) into the storage ring [1]. The high current and short bunch of the electron beams in the BEPCII injector linac causes the wakefield effects on the beam quality 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 by numerical beam modeling with LIAR (LInear Accelerator Research) code [2], 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 a large bunch charge of 2.5 nC and with 3 bunches in 1 ns beam pulae. The electron beam for injecting into the storage ring has a bunch charge of 0.35 nC, its wake effects can not be negligible too due to the long distance (~ 190 m) travel of the bunch in the linac. The positron beam has a bunch current of only 21 pC, its wake effects can be negligible by the beam modeling. To cure the wake effects on the beam quality dilutions some measures have been studied.

LONGITUDINAL WAKE EFFECTS

Single bunch longitudinal wake effect

A primary electron beam for the positron production comes from the electron gun with beam pulse length of 1 ns and pulse charge of 10 nC. With the pre-buncher, buncher and pre-accelerator which are operated at the same frequency as the one of the main linac (2856 MHz) and have the total bunching efficiency of 75%. The beam is bunched into three bunches, each has the bunch charge of 2.5 nC and beam energy of 40 MeV. Then these bunches are accelerated to about 250 MeV by 4 accelerating structures and transversely focused by two triple quadrupoles, 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 [3]. An zero-order minimum beam spot size on the target can be easily made by optimizing the beam optics with two triplet quadrupoles upstream the target. However, due to the low beam energy and large energy spread (usually about 5%) the chromatic effect in the quadrupole magnets may cause the beam spot size dilution [4]. Again, due to the low beam energy and large bunch charge, the longitudinal wake effect may cause an additional beam energy spread dilution leading to an additional chromatic effect and beam spot size dilution.

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

$$\frac{dE_h}{dz}=-\frac{Ne^2}{4}W_{//}(0) \quad \text{and} \quad \frac{dE_t}{dz}=-\frac{Ne^2}{4}W_{//}(0)-\frac{Ne^2}{2}W_{//}(d).$$

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

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 has shown that the optimized phase to minimize the bunch

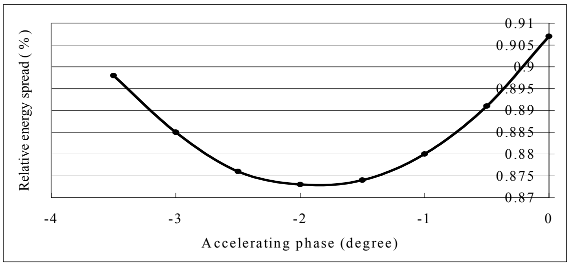

Figure 1: Bunch energy spread vs. accelerating phase.

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*wangsh@sun.ihep.ac.cn

energy spread for primary electron beam is -2° as shown in Figure 1, and -0.5° for the injection electron beam with bunch charge of 0.35 nC.

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]

$$\frac{dE}{dz}=\frac{dE_0}{dz}-\frac{W_{//}(s)Q_b\tau}{1-e^{-2\tau}}\left(\frac{1-e^{-2\tau}}{2\tau}-e^{-2\tau}\right)$$

where $Q_b = 2.5nC$ 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 kick plus its first derivative in position s along the bunch. For the BEPCII Linac's bunch train pattern (3 bunches in 1 ns beam pulse with bunch spacing 10.5 cm), we have [2]

$W_{//}(10.5cm) = 53.11V/pC/m$ and $W_{//}(21cm) = 40.47V/pC/m$.

Thus in the BEPCII Linac, the second bunch will meet a loaded gradient of 31.2 kV/m caused by the 1st bunch, and the 3rd bunch will meet a totally loaded gradient of 55.0 kV/m caused by the 1st and 2nd bunches. After traveling 12 m of the 4 accelerating structures, the maximum bunch to bunch energy variation will be 0.66 MeV, and the relative energy spread for the 250 MeV primary electron beam 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, let the 1st, the 2nd and the 3rd bunches enter the structures at 0.70 ns, 0.35 ns and 0 ns 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.

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 phasing error of $\pm 2^0$ have been taken into account.

Table 1: Longitudinal wake effects on the BEPCII-Linac

Beams	Beam Load. (LIAR)	Bunch E. spr. (SR wake) (2-particle)	Bunch E. spr. (Opti. phase)	Beam E. spr. incl. LR wake
250 MeV e-beam 2.5nC/b	-1.98 MeV	0.86 MeV (0.34 %)	0.97 % (-2^0)	1.03 %
1.89 GeV e-beam 0.34nC/b	-3.71 MeV	1.61 MeV (0.085 %)	0.371 % (-0.5^0)	0.39%

TRANSVERSE WAKE EFFECTS

Single bunch transverse wake effects

By the two macroparticle model, if the initial bunch offset x_0 at $z=0$, then at $z=s$, the tail particle's further offset caused by the wake $W_\perp(d)$ of head particle is [5]

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

where k is the quadrupole focusing strength, which is inversely proportional to the beam energy. For the BEPCII structure with the bunch length 3 mm, we have

$W_\perp(3mm) = 3.4kV/pC/m^2$.

With averaged focusing strength of the two triplets $\bar{k} = 0.86/m$, the averaged beam energy over the distance of about 20 m from pre-injector exit to the target $\bar{E} = 120MeV$, then we have $[\Delta x]_{\max} \approx 1.41x_0$. Hence the beam emittance and spot size at target may enlarged by a factor of about 1.4 caused by the single bunch wake effect.

To cure this effect an orbit correction scheme will be adopted. 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]. The well known BNS damping to cure the single bunch wake effect could not be applied in our case, since the linac is not long enough.

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 having 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 can also be represented by a

Table 2: Single bunch transverse wake effects

Initial beam offset (mm)	Nor. emitt. growth (%)		Beam size at target (mm)	
	no corr.	corr.	no corr.	corr.
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

point-like wake kick plus its first derivative in position d along the bunch. Thus for the BEPCII structure, one has

$$W_{\perp}(10.5cm) = 2.064kV/pC/m^2\ ; W_{\perp}(21cm) = 0.548kV/pC/m^2$$

To cure this BBU effect, except with 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. emitt. growth (%)		Beam size at target (mm)	
	no corr.	corr.	no corr.	Corr.
0.1	31	18	0.72	0.62
0.2	64	19	0.91	0.63
0.3	108	21	1.13	0.65
0.4	157	23	1.35	0.66
0.5	208	26	1.59	0.69
0.6	262	30	1.83	0.71
0.7	316	34	2.08	0.74
0.8	371	38	2.33	0.77
0.9	427	43	2.59	0.80
1.0	483	49	2.84	0.83

Note that Table 2 and Table 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. Our further studies have shown that if we control the initial beam offset within ±0.3 mm, and take into account the wake effects caused by the accelerating structure misalignment errors of 0.2 mm (1σ), the dispersive and chromatic effects caused by the quadrupole and BPM misalignment errors of 0.2 mm (1σ), and other jitter effects (e.g. RF power jitter of ±0.1 % and phasing error of $\pm 2^0$), then the final primary electron beam spot size on the positron production target will be about 1.0 mm with orbit correction, and the energy spread and emittance of the 1.89 GeV electron injection beam will meets its design goals of ±0.5 % and 0.25πmm-mrad, respectively, with orbit correction, as described in other papers [8].

SUMMARY

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. These are: 1)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; 2)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; 3)by controlling the accelerating structure offset, e.g. 0.2 mm (1σ) of alignment errors, and by employing the beam orbit correction scheme to cure the beam emittance, beam orbit and beam spot size dilutions caused by the single bunch and multi-bunch transverse wake effects.

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