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BEPCII Injector Linac Upgrade and Beam Instabilities

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The upgrade project of the Beijing Electron Positron Collider (BEPCII) and its injector linac is working well. The linac upgrade aims at a higher injection rate of 50 mA/min into the storage ring, which requires an injected beam with low emittance, low energy spread and high beam orbit and energy stabilities. This goal is finally reached recently by upgrading the linac components and by dealing with rich and practical beam physics, which are described in this study.

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The Beijing Electron Positron Collider (BEPC) is being upgraded to be a new collider BEPCII with two rings, aiming at a higher luminosity of $0.3 \times 10^{33} - 1.0 \times 10^{33}\,\mathrm{cm^{-2}s^{-1}}$, which is about two orders of magnitudes higher than the original one, and at a higher integrated luminosity. To meet these goals, its injector linac has been upgraded. The linac upgrade includes the beam energy upgrade from 1.30 GeV to 1.89 GeV for an on-energy injection into the ring, the positron beam current upgrade nearly from 4 mA to 40 mA with low energy spread and low emittance for a higher injection rate of 50 mA/min into the ring, and a stable operation beam performance for a higher integrated luminosity. According to the above-mentioned requirements, the linac has been greatly modified in all sub-systems.[1] After finishing the modifications the beam commissioning has been performed, and all the beam performance are met the design goals. The upgraded linac is being steady operated to provide the qualified injection beams for the BEPCII rings. On December 23, an acceptance test group organized by the Chinese Academy of Sciences has fully checked the linac beam performance. The measured beam energy, current, emittance, energy spread, orbit and energy stabilities are well reached their design goals, as shown in Table 1. One of the important goals of the linac upgrade aims at a higher injection rate of 50 mA/min into the storage ring, which requires the injected beam with low emittance, low energy spread and high beam orbit and energy stabilities. Rich and practical beam physics is presented in this Letter.

Table 1.Design and reached beam performance.

		Design	Reached[a]*	Original
Beam energy(GeV)		1.89	1.89	1.30–1.55
Current(mA)	e^+	37	66	3–5
	e^-	500	550	500
Emittance(1σ, mm·mrad)	e^+	0.40	0.35(X)-0.27(Y)	
	e^-	0.10	0.097(X)-0.079 (Y)	
Energy spread (1σ, %)	e^+	0.50	0.37	0.80
	e^-	0.50	0.30	0.80
Repetition rate (Hz)		50	50	12.5
Beam orbit instability (mm)		0.30	≤ 0.15	
Beam energy instability (%)		0.15	≤ 0.05	
e^+ injection rate (mA/min.)		50	61.5	1–3

[a]The reached values are confirmed by the acceptance test group organized by the Chinese Academy of Sciences.

A new electron gun with a thermionic cathode with high current of 10 A (10 nC, 1 ns FWHM) and low emittance has been constructed.[2] Just downstream the gun, a set of tuning tools is employed, including a pair of focusing coils, a couple of BPMs and orbit correctors, and beam profile monitors. By final tuning the downstream bunching system and two sets of the focusing triplets, an electron beam of about 7.9 A and 240 MeV can reach the positron conversion target, with small rms beam spot size of about 1.0 mm, so that a higher positron yield of 4.15% (GeV·e^-) was obtained. A new positron source with a flux con-

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centrator for a larger positron acceptance has been constructed.[3] By using a pulsed focusing coil (10 cm in length with tapered magnetic field of 4.5–0.5 T), a 7-m-long dc focusing coil (0.5 T) and some pairs of additional quads "riding" on the accelerating structures, a 80-mA 100-MeV positron beam was obtained at the positron source section exit. Followed by the accelerating structures, beam focusing quads and orbit correction system, a 1.89-GeV 61-mA positron beam was obtained at the linac exit, which is higher than the design current of 37 mA.

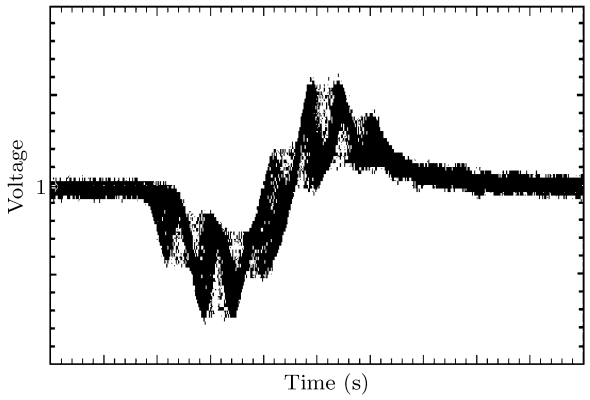


Fig. 1. Fluctuation of bunch distribution at the BPM14 (signals from 2 of 4 electrodes) observed by an oscilloscope.

For the beam energy upgrade from 1.30 GeV to 1.89 GeV, 16 rf power units are upgraded with higher power klystrons (E3730A-50 MW, TH2128C-45 MW and SLAC5045-65 MW) to replace the original one (HK-1-30 MW). The modulators are improved not only for the power upgrade from 80 MW to 110 MW, but also for improving the voltage instability to less than 0.15% by applying a De-Qing circuit and other measures for a steady beam energy and energy spread, combined with a new distributed phase control system. We will describe more details next concerning the beam energy instability. On the other hand, the averaged rf power was upgraded by a factor of 4, due to the necessary upgrade of the pulse repetition rate from 12.5 Hz to 50 Hz for a higher injection rate.

A new beam orbit correction system was applied with 16 strip line BPMs and correctors.[4] It is important to cure the transverse wake-field effect for the electron beam and the dispersive effect for the positron beam.[5] Due to a high impedance of the strip line BPM, they played an important role in the initial beam commissioning to find the beam position for the initial low beam current. The beam optics was optimized, by re-distributing 24 large aperture quads 'riding' on the accelerating structures downstream of the positron sources, to have a higher beam transmission toward the linac exit.

As an injector linac, one of the most important performances is its beam instability, particularly the orbit and energy instability. From March to June 2006, we suffered a serious beam orbit oscillation. This orbit oscillation was almost periodic with time seen by the BPMs, and the periods were changed frequently, say from a few seconds to a few hundreds of second in some hours. During the mini-workshop on the BEPCII linac in June 2006, the working group, which consists of BEPC and KEKB linac experts, has found the fluctuation of beam intensities at the 2nd beam current monitor just downstream the bunching system, caused by the electron gun trigger jitter (about 27 ps rms). Simultaneously a bunch distribution fluctuation was also found at BPM14 by observing its row signal with an oscilloscope, as shown in Fig. 1 These two phenomena indicate that both gun trigger timing jitter and non-synchronization with linac frequency (2856 MHz) may cause a bunch charge fluctuation and lead to a beam orbit oscillation via wake-field effect.

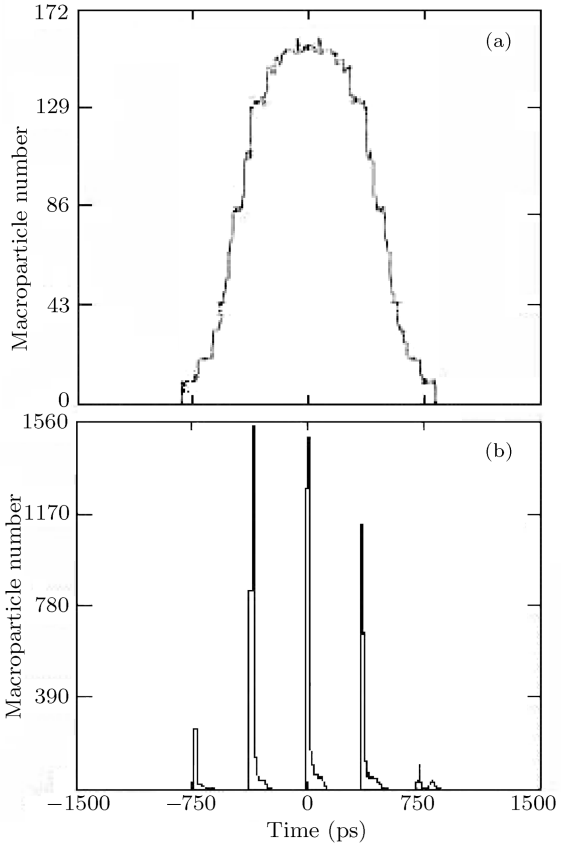


Fig. 2. Beam and bunch charge distribution before (a) and after (b) the bunching system.

Actually the electron gun works at 50 Hz repetition rate with a beam pulse length of 1.0 ns of FWHM and 1.6 ns at bottom. The pre-buncher and buncher work at the same frequency of the main linac (2856 MHz, time period of about 350 ps), so that there are about 5 bunches in each beam pulse downstream the bunching system. The simulated each bunch charge relative to the middle one is about 0.17, 0.83, 1.0, 0.65, and 0.06

without gun trigger jitter, as shown in Fig. 2. However, the gun trigger jitter may produce these bunch charge changes frequently, and lead to a beam pulse orbit oscillation via wake-field effect. It was observed that the higher the beam current from the gun, the stronger the oscillation amplitude in the beam orbit.

To cure this beam intensity fluctuation caused by the gun trigger jitter, an effective way is to synchronize the gun trigger with a 2856 MHz oscillator, which was realized by connecting two master oscillators of 2856 MHz and 499.8 MHz (ring rf frequency) at linac control room (and by reducing the gun trigger by a factor of $4^*7 = 17.85$ MHz). Soon after making this synchronization, the beam orbit fluctuation seen by the first 6 BPMs was suppressed down to about 1/5 of the original ones, say, about a few tenths of millimetre. However the beam orbit fluctuations in the remained downstream BPMs were still large, which was amplified mainly by the multi-bunch transverse wake-field effect due to the beam transverse offset. By applying the beam orbit correction, these fluctuations were also significantly reduced, and the remained oscillation was less than ±0.2 mm (rms), as shown in Fig. 3.[7]

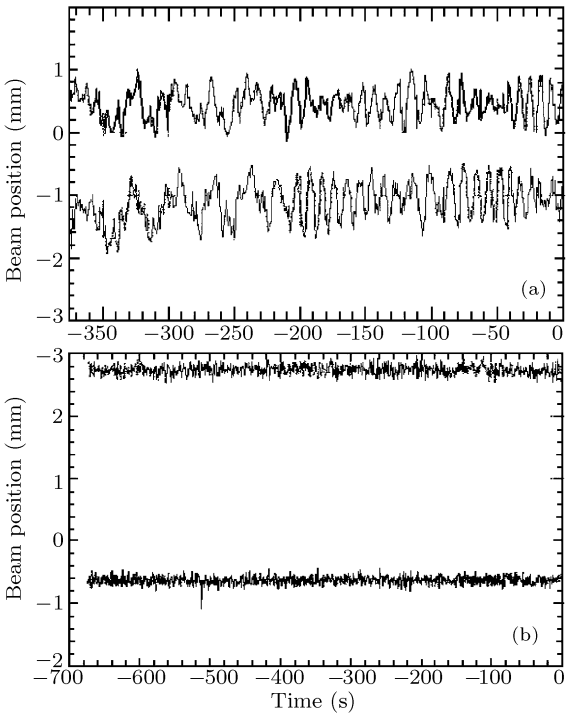


Fig. 3. Measured horizontal and vertical orbits at BPM14 with time before (a) and after (b) curing the orbit oscillation.

The beam energy instability can be easily measured by a BPM located at a large dispersion function in the beam transport line. Figure 4 shows the beam position varied within ±1.0 mm with time, seen by a BPM in the e-beam transport line, where the dispersion function is 2.0 m. It is indicated that the beam energy jitter is about ±0.05%, much smaller than the beam energy spread (±0.5%).[7]

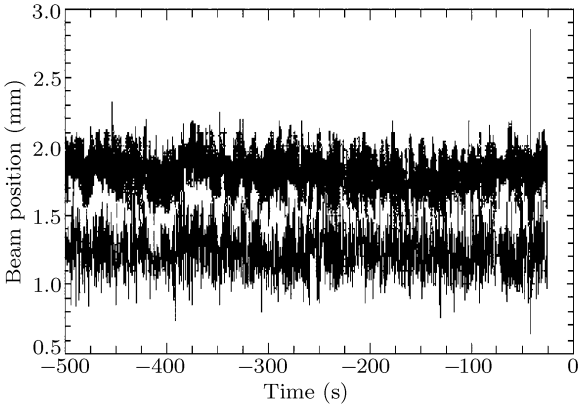


Fig. 4. Check the beam energy instability by observing a horizontal BPM signal (lower line) with time at large dispersion.

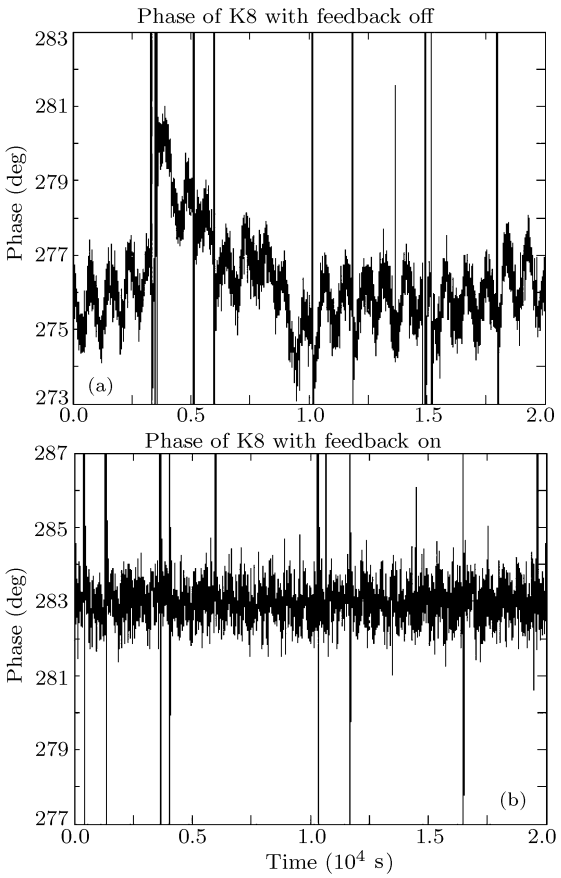


Fig. 5. Radio-frequency phase vs time at Klystron 8#: (a) phase control loop off, (b) phase control loop on.

Usually there are two jitters affected on the beam energy and energy spread. One is the accelerating phase shift due to, for instance, environment temperature change, and this is a slow effect, which can be cured by applying a phase control system. To cure this phase shift, a distributed phase control loop for

each rf power unit is established.[6,8] It consists of a phase reference line, a phase and amplitude detector (PAD) and a phase shifter at low rf level. Figure 5 shows the effect of the phase control loop at klystron 8#. One can see that the phase changes are 6.5° and 2° in six hours for the cases without and with control loop, respectively.

Another jitter effect on the beam energy and energy spread is the modulator voltage's jitter, and this is a fast effect and changed pulse to pulse. To cure the output voltage instability, the following three measures are used: by using De-Qing circuit to stabilize the charging voltage, by stabilizing the modulator dc voltage using a Thyristor voltage regulator with feedback control function, and by using high precision stabilizer to stabilize the klystron filament. These measures are very effective, so that the voltage instability can be controlled within $\pm 0.10\% - \pm 0.15\%$, and made a great contribution to the beam energy and energy spread steady.

In summary, the BEPCII injector linac has been successfully upgraded and steadily operated for about two years to provide the qualified electron and positron beams for the BEPCII rings, either for the ring commissioning, or for the synchrotron radiation operation for users. All beam performances, including the beam energy, current, emittance, energy spread, orbit and energy instabilities met the design goals. The positron injection rate was reached more than 60 mA/min, higher than the design value of 50 mA/min.

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