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Two-pulse acceleration for BEPC Ⅱ injector linac*

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Abstract : In order to double the injection rate of positron beam from the linac to the storage ring of BEPC Ⅱ, a two-pulse generation and acceleration scheme has been proposed. The two-pulse simulation by programs including LIAR , PARMELA , EGUN and TRANSPORT is described first and the method is applied in the beam dynamics studies of BEPC Ⅱ linac. The experiment of two-pulse acceleration was performed in BEPC Ⅱ linac and some preliminary results are obtained , which provides a good reference for further upgrading of BEPC Ⅱ injector linac.

Key words : Two-pulse ; BEPC Ⅱ linac ; Beam dynamics ; Numerical simulation

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In order to double the positron injection rate from the linac to the storage ring , a two-pulse acceleration scheme (two macro beam pulses with a time interval of 56.02 ns) has been proposed[1] for further upgrading of BEPC Ⅱ injector linac. At the present bunching system exit of BEPC Ⅱ linac , at least five bunches in one macro beam pulse are produced[2] , accordingly , no less than ten bunches need to be controlled in the real two-pulse acceleration mode , which makes it difficult to get the best beam characteristics. With the adoption of a new bunching system with two sub-harmonic bunchers(SHBs)[3] in BEPC Ⅱ linac , only a single bunch with higher bunch charge and better beam characteristics in one macro beam pulse is obtained at the exit of the bunching system , which facilitates the real operation of two-pulse mode.

1　Two-pulse generation and acceleration

In the new bunching system , two SHBs are introduced to replace the 2.856 GHz standing wave pre-buncher. The generation and acceleration of the two-pulse beams after adoption of the sub-harmonic bunching system is schematically illustrated in Fig. 1 , there is only a single bunch in one macro beam pulse.

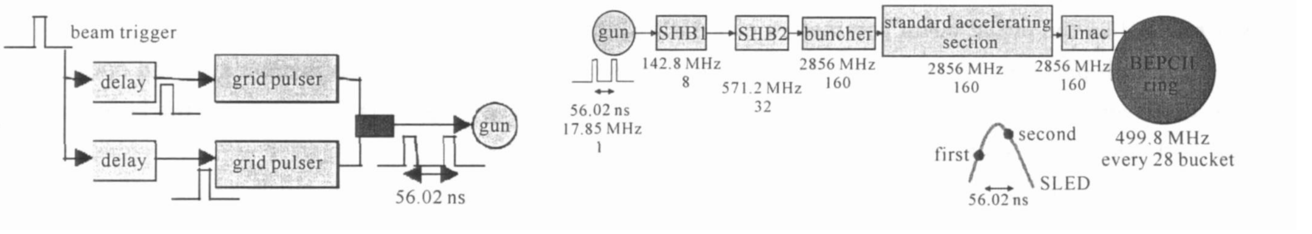

Fig. 1　Two-pulse generation and acceleration

2　Simulations

Up to now , it is hard to find a single program to simulate the beam dynamics of the whole electron linac including the gun , the bunching system and the accelerating sections , it is even harder to study the beam dynamics of two-pulse acceleration with a single program. In order to provide reference for BEPC Ⅱ linac upgrading project , several programs including EGUN , PARMELA , LIAR and TRANSPORT are adopted to simulate the beam dynamics of the two-pulse acceleration.

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2.1 Modifications of LIAR

In our simulation studies, the IHEP version of program LIAR 1.9[4-5] is used to simulate the beam dynamics at the downstream of the bunching system and evaluate the beam characteristics at the linac exit. Since the multi-bunch energy spread calculation method and the introducing method of long range wakefield in LIAR 1.9 can not be directly used in simulation, source code modifications of LIAR 1.9 have been done as follows:

(1) In LIAR 1.9, the multi-bunch energy spread is usually written as

$$\Delta E_{\mathrm{total}} = \frac{\sum_n Q_n \left[\sum_i \frac{q_{ni} E_{ni}^2}{Q_n} - \left(\sum_i \frac{q_{ni} E_{ni}}{Q_n} \right)^2 \right]^{1/2}}{\sum_n Q_n} \tag{1}$$

where $\Delta E_{\mathrm{total}}$ is the total energy spread of the pulse, Q_n is the total charge of bunch n in the pulse, q_{ni} and E_{ni} are the charge and energy of macro particle i in bunch n respectively. Essentially, the calculated energy spread by Eq. (1) is still the energy spread of one single bunch, which can not reflect the energy spread increase caused by the energy difference between two bunches. To evaluate the multi-bunch energy spread properly, a new equation has been applied

$$\Delta E_{\mathrm{total}} = \left[\sum_n \sum_i \frac{q_{ni} E_{ni}^2}{\sum_n Q_n} - \left(\sum_n \sum_i \frac{q_{ni} E_{ni}}{\sum_n Q_n} \right)^2 \right]^{1/2} \tag{2}$$

(2) When long range wakefield is introduced in the beam dynamics simulation of one pulse with program LIAR 1.9, only the wakefield effect of bunch n on bunch $n+1$ is considered, while that of bunch n on bunch $n+2$ and the other downstream bunches is not considered. In order to investigate the effect of long range wakefield more generally, long range wakefield effect in LIAR 1.9 has been modified to take into account the wakefield effect of bunch n on all the downstream bunches.

2.2 Simulation method

To find an appropriate method to simulate the beam dynamics of two-pulse acceleration with one or more bunches in one pulse in the whole linac, the following methods are applied:

(1) Program EGUN[6] is used to simulate the beam optics in the electron gun. Correspondingly, the transverse beam parameters including the emittance and the twiss parameters at the electron gun exit, which will be used as the initial beam parameters of PARMELA[7], are obtained.

(2) With program PARMELA, the beam dynamics of the bunching process is simulated and optimized, then the beam parameters including the emittance, the bunch charge, the twiss parameters, the beam energy and the beam energy spread at the bunching system exit are acquired.

(3) When the relativistic velocity of electron beams is almost equal to 1, the space charge effect can be neglected, thus program TRANSPORT optimizes the beam optics from the bunching system exit to the linac exit. The beam parameters calculated by PARMELA serve as the input beam parameters of code TRANSPORT[8] in simulating and optimizing the lattice from the bunching system exit to the lianc end, finally beam optics with the optimized lattice is achieved.

(4) In high energy linacs, wakefield is the main effect on the beam characteristics. In addition, the beam pulse interval in the two-pulse mode is usually at the level of nanosecond, and the wakefield of the first pulse will affect the second pulse. Consequently, the wake potential, especially the long range wake potential in the accelerating structures should be calculated before simulating the two-pulse acceleration. Analytical methods and computer codes such as ABCI[9], MAFIA[10] and so on can be used to calculate the wake potential. For simulation of the two-pulse acceleration in BEPC Ⅱ linac, the wake potential is estimated precisely with the method in Ref. [11].

(5) In addition to the beam parameters at the bunching system exit, the wake potential in the accelera-

ting structures and the beam optics with the optimized lattice are all obtained, the beam dynamics of the two-pulse acceleration at the downstream of the bunching system is simulated with the modified IHEP version of LIAR 1.9. In the studies of the two-pulse acceleration with LIAR, if there is only one single bunch in one macro beam pulse, which is the case of BEPC Ⅱ linac with SHBs, LIAR can be directly used. However, for studies of two-pulse acceleration for BEPC Ⅱ linac without SHBs, the simulation process is divided into three steps: a) The simulation of one pulse can be done with LIAR directly[12]; b) If one pulse is regarded as a large macro bunch with the total charge of the bunches in the pulse the two pulses can be regarded as two large macro bunches, then the simulation of the two large macro bunches can be performed by LIAR; c) After the simulations of one bunch and two large macro bunches, the total beam characteristics dilution of the two-pulse caused by any kind of error or jitter effects[13] can be summed up as follows

$$\Delta_{\mathrm{total}} = \sqrt{\Delta^2_{\mathrm{one\_pulse}} + \Delta^2_{\mathrm{two\_macro\_bunches}}} \tag{3}$$

where Δ_{total} is the total beam characteristics dilution such as emittance, energy spread and so on, $\Delta_{\mathrm{one\_pulse}}$ and $\Delta_{\mathrm{two\_macro\_bunches}}$ are the beam characteristics dilutions caused by error or jitter effects on the one pulse and the two large macro bunches respectively.

It is worth noting that the effect of the first beam pulse on the second beam pulse in the bunching process is neglected in our method, since the energy and the pulse charge differences caused by beam loading in standing wave cavities[14] and the wakefield for particle beams with $\beta \leq 1$[15] are relatively small, and can be further mitigated to a very low level by adjusting the gun grid pulser voltage and the beam pulse timing respectively[16].

2.3 Simulation results

With our method, the beam dynamics of two-pulse acceleration for 2 A (averaged current)/3.2 A (peak current) electron beam in BEPC Ⅱ Linac with/without SHBs has been studied systematically. Table 1 shows the beam characteristics parameters calculated with EGUN and PARMELA at the gun exit and the bunching system exit for BEPC Ⅱ pre-injector with/without SHBs[3]. Fig.2 shows the linearly approximated beam optics downstream of the bunching system optimized by TRANSPORT without considering any wakefield effects and any kind of error or jitter effects. Table 2 shows the final beam characteristics simulation results at BEPC Ⅱ linac with/without SHBs exit for the beam dynamics of two-pulse acceleration when 0.3 mm initial beam offset, 0.2 mm accelerating structure and quadruple misalignment, ±2° accelerating phase drift and ±0.1% modulator's high voltage jitter were employed. In addition, in order to compensate the bunch energy spread caused by short range wakefield, the accelerating phase was optimized, i.e., the bunch center was put off-crest of the accelerating wave, so that the particles in the tail and head parts would have higher and lower energy gain, respectively[12].

Table 1 Beam characteristics calculated with EGUN and PARMELA at electron gun exit and bunching system exit for 2 A electron beam

gun exit			bunching system exit		
parameter	without SHBs	with SHBs	parameter	with SHBs	without SHBs
energy/keV	150		energy/MeV	56.19	53.39
intensity/(nC/pulse)	3.2		energy spread(±5 ps)/MeV	±3.58	±3.70
pulse width(bottom)/ns	1.6		intensity(±15 ps)/(nC/pulse)	2.56	3.19
pulse width(FWHM)/ns	0.95		bunch number in one pulse	5	1
emittance(2σ)/(mm-mrad)	30.78		intensity(±5 ps)/(nC/bunch)	0.16,0.56 0.71,0.56,0.18	3.10
α	2.13		pulse length(bottom)/ps	>1 400	10
β/(m/rad)	0.34		bunch length(bottom)/ps	10	10
γ/(rad/m)	16.45		bunch interval/ps	350	
			emittance(1σ)/(mm-mrad)	1.18	1.05
			α	-0.12	0.06
			β/(m/rad)	1.50	1.12

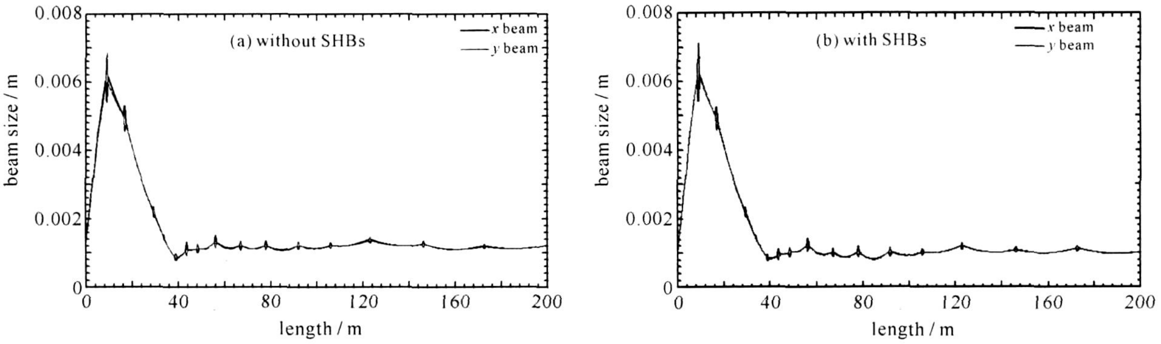

Fig. 2 Linearly approximated beam optics downstream of the bunching system for BEPC Ⅱ linac

Table 2 Simulation results at BEPC Ⅱ Linac exit with/ without SHBs of two-pulse acceleration beam dynamics for 2 A electron beam

	without SHBs		with SHBs	
	single pulse	two pulses	single bunch	two bunches
bunch length(bottom) / ps	10		10	
pulse length(bottom) / ps	> 1 400		10	
intensity(±15 ps) / (nC/ pulse)	< 2.56		< 3.19	
intensity(±5 ps) / (nC/ bunch)	< 0.16 , < 0.56 , < 0.71 , < 0.56 , < 0.18		< 3.10	
energy spread(±5 ps) / %	±(0.71 ±0.06)	±(0.77 ±0.06)	±(0.53 ±0.06)	±(0.63 ±0.06)
emittance (1σ, no correction) / (mm ·mrad)	0.11 ±0.04	0.16 ±0.04	0.32 ±0.04	0.43 ±0.04
emittance (1σ, correction) / (mm ·mrad)	0.05 ±0.02	0.05 ±0.02	0.11 ±0.02	0.13 ±0.02

Analyzing Table 1 and Table 2 gives the following conclusions:

(1) The replacement of bunching system without SHBs by that with SHBs can reduce the number of bunches in one macro beam pulse, which can facilitate the operation of the two-pulse acceleration.

(2) For the 2 A electron beam, the adoption of a two-pulse acceleration scheme will result in a small energy spread increase and a large emittance dilution at the linac exit. While with the employment of an effective beam orbit correction scheme[17], the emittance dilution can be controlled to an intermediate level, which can meet the requirement of the storage ring for the electron beam[1].

(3) Although the beam energy spread of the 2 A beam at the linac exit becomes smaller for BEPC Ⅱ linac with SHBs, the effect of the SHBs on the energy spread reduction is not obvious. In BEPC Ⅱ injector linac, the beam energy spread is mainly decided by the bunch length. Whether the SHBs is adopted or not, the bunch length will be about 10 ps, i.e., the SHBs can not produce a bunch much shorter than 10 ps. If SHBs is adopted, the long range wakefield effect on the energy spread in one pulse can be wiped off, but due to the high bunching efficiency and the bunch charge increase in one bunch, the short range wakefield effect on the energy spread will increase, as a result, the effect of SHBs on the beam energy spread at the linac exit will not be obvious.

(4) The emittance at BEPC Ⅱ linac with SHBs exit is about 3 times that at the linac exit without SHBs, i.e., the SHBs have a negative effect on the emittance of the 2 A beam, which is mainly caused by the optimization of the beam optics at the downstream of the bunching system. If a better optimization method is employed, the negative effect might be relatively small. In the calculation of beam optics by TRANSPORT, the optimized lattice is obtained by linear approximation and without considering the effect of the beam charge (not space charge effect) on the optics. In addition, when the optimized lattice is used as input of LIAR, the higher the charge contained in one bunch, the higher the value of the beam optics mismatch factor B_{mag}, hence the mismatch factor for the linac with SHBs will be higher than that of the Linac without SHBs.

Table 3 shows the simulation results of 1 A (averged current) electron beam when 0.9 mm initial beam offset, 0.6 mm accelerating structure and quadruple misalignment, ±2 °accelerating phase drift and ±0.1 % modulator's high voltage jitter were employed, according to the alignment and real operation status of BEPC

Ⅱ linac without SHBs. Either linac with or without SHBs can meet the requirement of the storage ring for the electron beam[1] and has almost the same energy spread and beam emittance at the linac exit due to the small difference between the mismatch factors of the beam optics, while the linac with SHBs has a shorter beam pulse length of 10 ps rather than a length longer than 1.4 ns and higher beam current at BEPC Ⅱ linac exit.

Table 3 Simulation results at BEPC Ⅱ Linac exit with/ without SHBs of the two-pulse acceleration beam dynamics for 1 A electron beam

	without SHBs		with SHBs	
	single pulse	two pulses	single bunch	two bunches
bunch length (bottom) / ps	10		10	
pulse length (bottom) / ps	> 1 400		10	
intensity (±15 ps) / (nC/ pulse)	< 1.30		< 1.52	
intensity (±5 ps) / (nC/ bunch)	< 0.07, < 0.35, < 0.45, < 0.35, < 0.08		< 1.43	
energy spread (±5 ps) / %	±(0.65 ±0.03)	±(0.67 ±0.03)	±(0.59 ±0.03)	±(0.61 ±0.03)
emittance (1σ, no correction) / (mm · mrad)	0.09 ±0.02	0.12 ±0.02	0.14 ±0.02	0.16 ±0.02
emittance (1σ, correction) / (mm · mrad)	0.04 ±0.01	0.04 ±0.01	0.03 ±0.01	0.03 ±0.01

Comparing Table 2 and Table 3, it is found that the lower the beam current, the better the beam characteristics at the linac exit, the smaller the beam characteristics difference between the single-pulse and the two-pulse operation modes, the looser the alignment tolerance of the components in the accelerator. It also proves that it is better to use lower beam current to get a better beam characteristics for the electron injection mode in the real operation of BEPC Ⅱ linac without SHBs.

3 Experiments

Two-pulse generation and acceleration experiment was performed in BEPC Ⅱ linac without SHBs, and there were at least 5 bunches in one pulse and 10 bunches in two pulses. Fig. 3 shows a typical waveform of the final four beam current monitors (BCT8 to BCT11) for the two-pulse acceleration mode. The time interval between the two pulses was 56.02 ns and was adjusted with a step of 20 ps. BCT11 was placed at the linac end. The amplitudes of BCT11 for the two pulses were 33 mV and 40 mV, corresponding to about 500 mA and 600 mA beam peak current respectively. It is known that if the initial currents of the two beam pulses have the same value, at the linac end the current of the second pulse should be lower than that of the first pulse[14], but in our experiment it is just the opposite, which was caused by different grid pulser voltages at the electron gun. For the first pulse, the pulser voltage was 271.8 V, corresponding to an initial averaged current of 1.1 A, while for the second pulse the voltage and current were 282.1 V and 1.3 A, respectively.

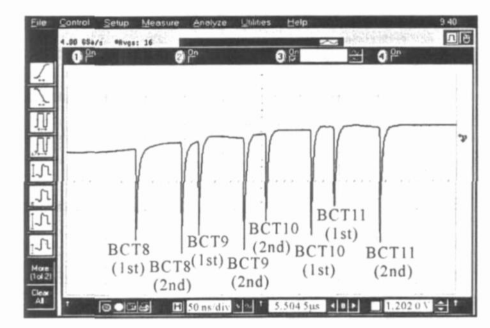

Fig. 3 Signals of BCT8 to BCT11 on the oscilloscope

The beam emittance was measured for both single-pulse and two-pulse operation modes, and the measurements were done by the Q-scan method[18] at the linac end. For the single-pulse mode, the measured horizontal and vertical emittances are about 0.082 ±0.010 (mm · mrad) and 0.096 ±0.017 (mm · mrad) respectively, while they are about 0.086 ±0.011 (mm · mrad) and 0.141 ±0.036 (mm · mrad) for the two-pulse mode. The measured vertical emittance is larger than the horizontal emittance for both operation modes, which is caused by different beam optics matching status in the two directions. Comparing the measured emmitances with the simulated ones in Table 3 for 1 A electron beam, it can be found that they are consistent on the whole. In addition, there is a small difference between the emittance of the single-pulse mode and that of the two-pulse mode, and the beam characteristics of the two modes will have a small difference for a beam current lower than 1 A (averaged). The positron beam (whose current is much lower than 1 A) injection rate can be finally increased and doubled by adoption of the new SHBs and the two-pulse acceleration scheme.

4 Conclusion

In order to provide reference for further upgrading of BEPC Ⅱ injector linac, beam dynamics of two-pulse acceleration has been studied, a two-pulse experiment has been performed, some preliminary results are obtained. Although there is still some difference between the simulation and measurement results, they are consistent on the whole. In addition, it is indicated that the adoption of the two-pulse scheme is not for electron injection, but for the doubling and increasing of the primary electron beam charge to increase the positron yield and the position injection rate to the ring. In BEPC Ⅱ injector linac, the charge contained in the positron bunch is much smaller than that in the electron bunch. In addition, the beam characteristics of the primary electron beam with SHBs is better than that without SHBs, which can be known from the better beam characteristics at the SHBs exit and the negligible wakefield effect along the 12 m long beam orbit between the bunching system exit and the positron target. In conclusion, the adoption of SHBs can enhance the positron beam performance at the linac exit and facilitate the real operation of the two-pulse mode.

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BEPC Ⅱ直线加速器的双脉冲加速研究

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摘　要: 为了将BEPC Ⅱ直线加速器的正电子注入速率提高到单脉冲运行时的两倍左右, 提出了双脉冲产生和加速的方案。对BEPC Ⅱ直线加速器双脉冲加速的束流动力学进行了模拟, 首次给出了双脉冲的模拟方法。此外, 还在BEPC Ⅱ直线加速器上进行了双脉冲加速的初步实验研究, 为以后BEPC Ⅱ直线加速器的进一步改造提供了参考。

关键词: 双脉冲; BEPC Ⅱ直线加速器; 束流动力学; 数值模拟