

DESIGN OF BUNCH LENGTHENING SYSTEM IN ELECTRON LINAC*

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Abstract

The High Energy Photon Source (HEPS) is a 6-GeV, ultralow-emittance light source to be built in China. The injector is composed of a linac and a full energy booster. To increase the threshold of TMCI in the booster, the HEPS linac design has been evolved with several iterations. The important middle-version design is a 300 MeV linac with rms bunch length larger than 20 ps. One bunch lengthening system is proposed and discussed in this paper.

INTRODUCTION

The High Energy Photon Source (HEPS) is a 6-GeV, ultralow-emittance storage ring light source to be built in China. The HEPS is composed of a 500-MeV linac [1], a full energy booster [2] with 1 Hz repetition frequency, a 6-GeV storage ring [3] and transport lines. The bunch charge threshold of TMCI of booster is a very important issue. A FODO lattice design of the booster is chosen after iterations. One important guidance to the lattice optimization of the booster is to increase the momentum compact which influences TMCI threshold. The HEPS linac also has been iterated for several times to meet the requirements that can increase TMCI threshold of booster. At the early stage, the HEPS linac was an S-band (2998.8 MHz) normal conducting 300 MeV linac with sub-harmonic bunching cavities, one macro bunch per pulse and bunch length in 5 ps, namely V1 in this paper. With the study of TMCI the requirements for linac have been changed. The pulse mode chose multi-macro-bunch per pulse using 2998.8 MHz pre-buncher instead of sub-harmonic cavities. The rms bunch length was changed from 5 ps to 20 ps by introducing bunch lengthening system. So the middle version design of HEPS linac is a 300 MeV linac with multi-macro-bunch per pulse and rms bunch length in 20 ps, namely V2 in this paper. One bunch lengthening system was included in the

design. With in-depth study and experts' suggestion, the 500 MeV linac is more beneficial for physical design. After comprehensive consideration the HEPS linac is adopted at last, which of energy is 500 MeV, pulse mode is multi-macro-bunch per pulse and rms bunch length is 5 ps [1] without bunch lengthening system, namely V3 in this paper. The evolution of HEPS linac layout is shown in Fig. 1.

As a very important stage the middle version scheme (V2) of linac was carefully designed. The main parameters are shown in Table 1, which is composed of gun, bunching section, accelerating section and bunch lengthening section. In this paper the design of bunch lengthening system is presented.

Table 1: Main Parameters of 300 MeV Linac

Parameter	Unit	Value
Frequency	MHz	2998.8
Energy	MeV	≥ 300
Bunch charge	nC	≥ 2.5
Macro-bunch length	ps	≥ 20
Emittance	nm	≤ 70
Energy spread	%	0.5

THEORETICAL ANALYSIS

According to basic theory and the transfer matrix, the particle position can be calculated by the following formula:

$$s_o = s_i + R_{56}\delta_i \quad (1)$$

Where s_o is the output longitudinal coordinate, s_i is the input longitudinal coordinate, δ_i is input energy spread.

If the input beam is similar to linear distribution in longitudinal phase space and can be expressed as:

$$\delta_i = g s_i. \quad (2)$$

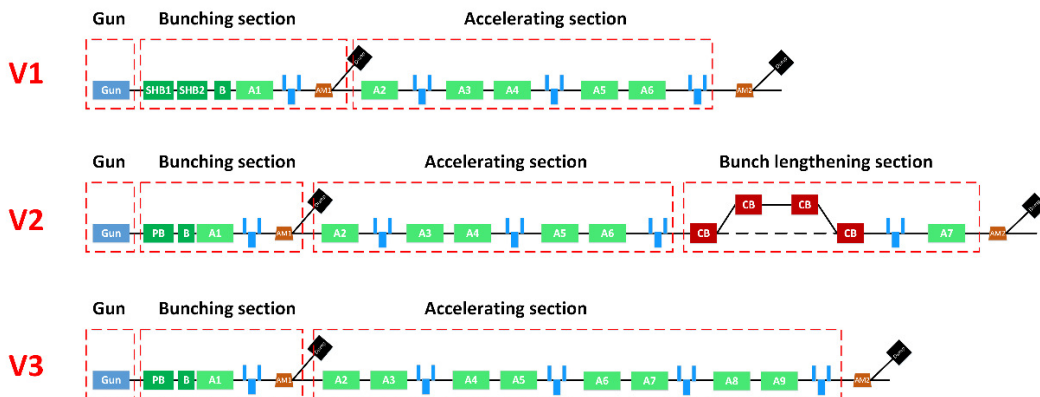


Figure 1: The evolution of HEPS linac layout.

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Where g is momentum chirp. Then Equation (1) can be expressed as:

$$s_o = s_i(1 + gR_{56}). \quad (3)$$

Assuming R_{56} is negative:

- If g is negative, the bunch is lengthened.
- If g is positive, the bunch is compressed.

According to the above analysis, one system with suitable R_{56} and momentum chirp g can lengthen bunch length. So a chicane system would be introduced to lengthen the bunch. If one wants to depress the emittance growth included by CSR, double C-Chicane can be adopted. If one wants to get larger R_{56} , S-Chicane can be adopted. To make the bunch lengthening system simple, C-Chicane is adopted and the schematic diagram of bunch lengthening system is shown in Fig. 2. After the chicane there is a cavity to modulate longitudinal phase space distribution.

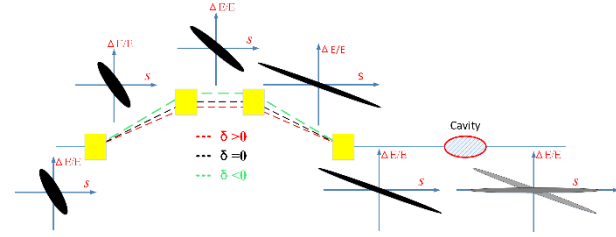


Figure 2: The schematic diagram of bunch lengthening system.

The chicane is achromatic. As shown in Fig. 3, the four dipoles are the identical rectangular type and can be driven by one power supply. Charged particles with different energies have different trajectories in the chicane system. In Fig. 3, θ is the deflecting angle, a and b are the two characteristic distance. After theoretical derivation, we can get the following formulas:

$$R_{56} = \frac{ds}{d\delta} = 4\rho[\theta - \tan\theta] - 2a \frac{\sin^2\theta}{\cos^3\theta} \quad (4)$$

$$D_{x,mid} = 2\rho\left(\frac{1}{\cos\theta} - 1\right) + a \frac{\sin\theta}{\cos^3\theta} \quad (5)$$

$$H = 2\rho(1 - \cos(\theta)) + a \tan(\theta) \quad (6)$$

$$L = 4\rho \sin(\theta) + 2a + b. \quad (7)$$

Where ρ is radius of deflection, $D_{x,mid}$ is the dispersion at the middle drift, H is the height or width and L is the length of chicane.

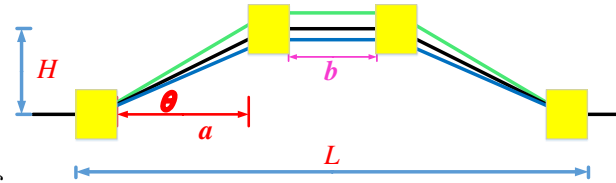


Figure 3: The layout and parameters of chicane.

To investigate the parameter importance, we study the coefficient of Eq. (4) ~ Eq. (7) on ρ and a with different angle, which is shown in Fig. 4. According to the analytical results, one can know that the deflecting angle is the most critical parameter and a is more important than ρ . To obtain

large absolute value of R_{56} , larger deflecting angle and larger a is preferred, but the dispersion and chicane size should be controlled carefully.

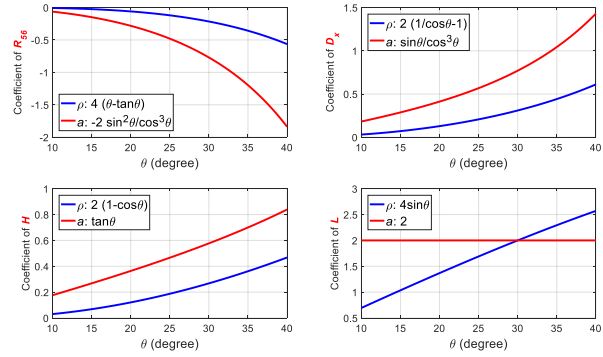


Figure 4: The coefficient on ρ and a with different angle.

According to Eq. (3), to lengthen bunch length we need negative momentum chirp ($g < 0$) if R_{56} is negative. After theoretical derivation, one can get the energy spread at the exit of accelerating structure as following expression:

$$\delta_o = \frac{E_i}{E_o} \delta_i + \frac{2\pi e V f \cos\phi_s}{c E_o} s_i. \quad (8)$$

$$E_o = E_i + eV \sin\phi_s$$

Where E_i is the input energy, E_o is the output energy, V is the total voltage of the accelerating structure, f is the frequency and c is velocity of light. According to the Eq. (8), if negative momentum chirp is needed, the synchronous phase should be larger than 90° . Here short-range longitudinal wakefield is an important issue with high bunch charge and affects the energy spread.

PHYSICS DESIGN

For the HEPS linac V2 version, the energy is 300 MeV and the required rms bunch length is larger than 20 ps which is 6 mm. According to Eq. (1), if the energy spread is 1%, the required absolute value of R_{56} is larger than 0.6 m. In the linac design the accelerating section can modulate longitudinal distribution to the required distribution. The distribution at the bunching section exit in longitudinal plane is shown in Fig. 5. According to Eq. (8), one can get the synchronous phase is 100° and considering the wakefield the synchronous phase is set as 98° .

Expect the requirement that the absolute value of R_{56} is larger than 0.6 m, the dispersion should be smaller than 1 m, chicane width H should be smaller than 0.8 m limit by the linac tunnel and the length of chicane is shorter than 5.5 m. At the middle drift there is a movable collimator to reduce the longer energy tail. To increase the collimation efficiency, the dispersion should be controlled within reasonable value before collimator and the normalized dispersion should be as large as possible.

In order to achieve the above goal, parameters scanning is presented where parameter b is 0.6 for collimator installing and only affect the length L , shown in Fig. 6 and Table 2. With comprehensive considering of magnet design and physic results, the second case (case 2) is preferred.

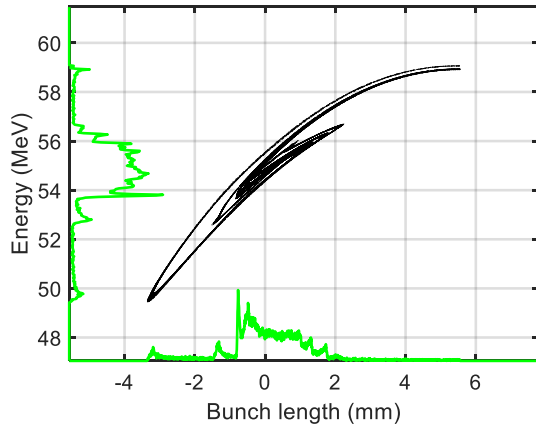


Figure 5: The longitudinal distribution at bunching section exit.

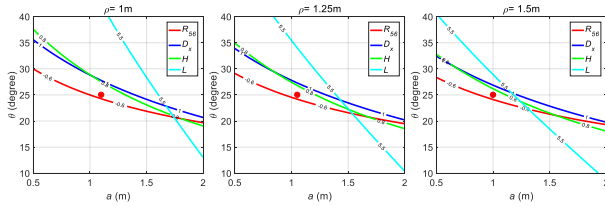


Figure 6: Parameters choice region at different case.

Table 2: Parameters at different cases

Parameter	Unit	Case 1	Case 2	Case 3
ρ	m	1.00	1.25	1.50
θ	°	25	25	25
a	m	1.10	1.05	1.00
b	m	0.60	0.60	0.60
R_{56}	m	-0.65	-0.65	-0.66
$D_{x,mid}$	m	0.83	0.86	0.88
H	m	0.70	0.72	0.75
L	m	4.49	4.81	5.14
B	T	1.000	0.800	0.667

SIMULATION RESULTS

Based on the above analysis and design, the simulation was performed preliminary with Elegant [4]. The optics functions along accelerating section and bunch lengthening section are shown in Fig. 7 and can meet the physics requirements.

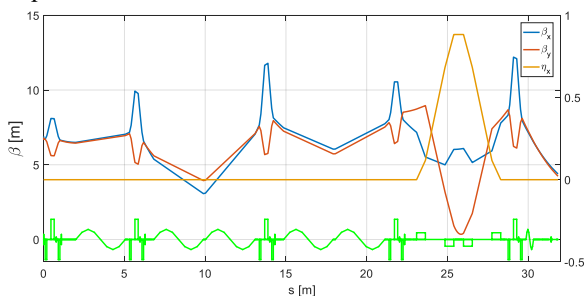


Figure 7: Optics functions along the linac.

The energy spread and bunch length along the linac and beam distribution at the bunch lengthening section exit in longitudinal plane is shown in Fig. 8. According to the study of TMCI, longer bunch length and larger energy spread is preferred. Considering the energy acceptance of booster, the energy spread is designed to slightly smaller than 0.5%. For the linac the energy spread can be reduced to lower value. The bunch length at exit of linac is about 22 ps that can meet the requirement. In the linac there are five macro-bunches, to better display the bunch length, the beam distribution is Fig. 8 is the overlaying results.

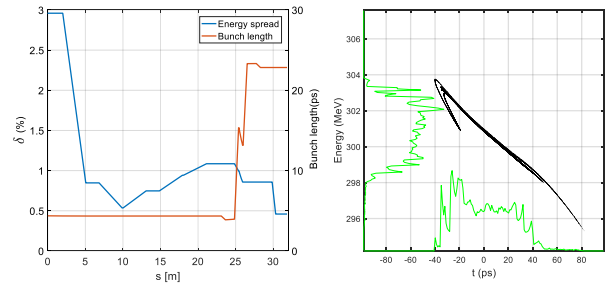


Figure 8: Energy spread and bunch length along the linac (left) and beam distribution at the bunch lengthening section exit (right).

CONCLUSION

To increase the TMCI threshold of HEPS booster and to fulfil the injection requirement of storage ring, the linac design is updated. The design of bunch lengthening system in the second linac scheme is proposed. The theoretical analysis, physics design and simulation of the bunch lengthening system is presented in this paper. All the design requirements can be fulfilled after the optimizations.

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