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PERFORMANCE OPTIMIZATION OF LOW-EMITTANCE DC-SRF INJECTOR USING Cs_2Te PHOTOCATHODE*

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Abstract

A low-emittance DC-SRF injector (DC-SRF-II) is under construction at Peking University, in the earlier design of which K_2CsTe photocathode was chosen. Recently we changed the cathode to Cs_2Te which is more widely used nowadays, and carried out a detailed performance optimization. In this paper, we present our latest simulation results, which show that an emittance under 0.5 mm−mrad can be achieved at the bunch charge of 100 pC.

INTRODUCTION

DC-SRF photocathode injector, which combines a DC gun and a superconducting radio-frequency (SRF) cavity [1, 2], is capable of generating CW electron beams. It was brought into stable operation in 2014 [3] at Peking University. In order to accommodate the requirement of electron beam with higher bunch charge (100 pC) and lower emittance (< 1 μm), an upgraded version of DC-SRF injector (referred to as "DC-SRF-II" herein) adopting K_2CsTe cathode has been designed and the fabrication is under way now.

In this paper, we present the simulation study of the DC-SRF-II injector with the extensively used Cs_2Te cathode. To investigate its performance as an electron source for CW XFEL, the injector beamline was designed for optimized projected emittance, bunch length, and higher-order energy spread. The multi-objective optimization algorithm was implemented to obtain the global optimal solution.

INJECTOR LAYOUT

A sketch of the DC-SRF-II injector beamline is shown in Fig.1. The photocathode (Cs_2Te) is located at the entrance of the DC gap, soon after which a 1.3 GHz, 1.5-cell SRF cavity boosts the electron beam to a few MeV. Two solenoids downstream the DC-SRF-II injector confine the beam size and compress/compensate the transverse emittance. Following the solenoids is an electron buncher, which is composed of a 1.3 GHz, 2-cell cavity operated around zero crossing phase and a third-harmonic cavity introduced to improve the bunching performance. A standard cryomodule comprising eight 1.3 GHz, 9-cell cavities (referred to as "injection linac" later on) finally accelerates the average energy up to above 100 MeV, followed by a third-harmonic linearizer (four 3.9 GHz, 9-cell cavities) to remove the lower-order energy spread.

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The fields of the DC structure, the SRF cavity, and the solenoids are cylindrically symmetric in first order. Our study indicates that the higher-order effects that break the symmetry only have insignificant impact on the emittance, bunch length, and higher-order energy spread herein. Therefore, this paper focuses on the cylindrically symmetric issues. The higher order effects, such as those due to the dipole filed of RF coupler and off-axis drive laser, will be discussed elsewhere.

OPTIMIZER DESCRIPTION

Optimization Goals

XFEL operation requires electron beam with low emittance and high peak current. At the exit of injector beamline, the electron beam should have a low emittance and a moderate bunch length ~ 10 picoseconds. The electron beam from the injector beamline will be further accelerated by main linacs and compressed by magnetic compressors to achieve the required energy and peak current. The energy distribution of electrons within a bunch [$E(z) \sim E_0 + c_1 z + c_2 z^2 + O(z^3)$, where z is the position within the bunch] has significant impact on the performance of compression. Its linear and quadratic correlation terms (c_1 and c_2) can be largely eliminated with properly set rf phases and amplitudes of the linac and linearizer (harmonic cavity). The higher-order energy spread $O(z^3)$, however, needs to be suppressed in the injector beamline.

Boundary Conditions

In the optimization, the thermal emittance coefficient of Cs_2Te cathode was assumed to be 1.0 mm−mrad/mm. The drive laser pulse has a plateau distribution with the length of 24 ps and rise time of 2 ps, which can be achieved via coherent pulse stacking [4]. The transverse distribution of the laser is a 2D-Gaussian function truncated at 1 sigma. The initial bunch charge is 100 pC.

The first solenoid downstream the DC-SRF-II injector (see Fig. 1) will be fixed at 1 m, mainly limited by the length of the cryomodule. The position of the second solenoid and the strength of both solenoids need to be optimized. Other knobs used in the optimization, including the amplitude and phase of 1.5-cell cavity field, are given in Table 1. The DC voltage was fixed at 100 kV.

Optimization Process

For the optimization, the MOGA-II algorithm [5] was chosen to drive ASTRA [6] simulations. Since more than one objectives need to be optimized, the result is not a single

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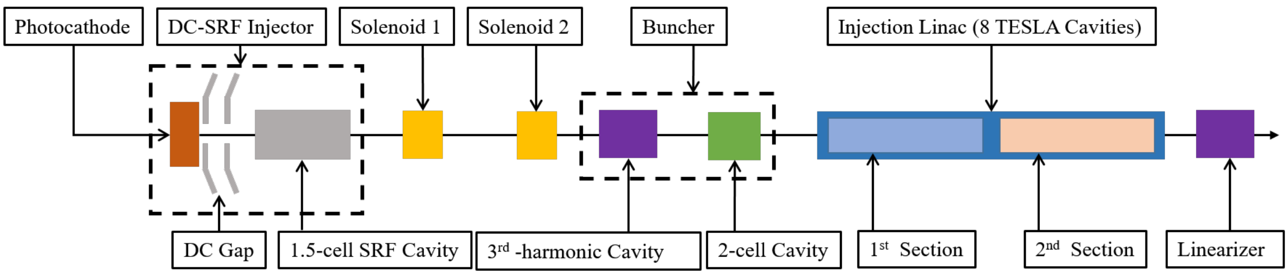

Figure 1: A schematic layout of the DC-SRF-II injector beamline. The drive laser system is not shown.

Table 1: Knobs used for DC-SRF-II injector optimization. All positions refer to the exit of the previous element.

Knob	Range	Unit
1.5-cell phase	[-30,10]	degree
1.5-cell amplitude	[20,28]	MV/m
Solenoid 1 strength	[0.01,0.12]	T
Solenoid 2 strength	[0.01,0.12]	T
Solenoid 2 position	[0,3]	m
3^{rd}-harmonic cavity position	[0,2]	m
3^{rd}-harmonic cavity amplitude	[0,5]	MV/m
3^{rd}-harmonic cavity phase	[-200,-160]	degree
2-cell position	[0,2]	m
2-cell amplitude	[3,10]	MV/m
2-cell phase	[-120,-80]	degree
1^{st} section position	[0,2]	m
1^{st} section amplitude	[20,28]	MV/m
1^{st} section phase	[-6,6]	degree
2^{nd} section amplitude	30	MV/m
2^{nd} section phase	[-10,10]	degree
Linearizer position	17	m
Linearizer amplitude	[5,15]	MV/m
Linearizer phase	[-190,-150]	degree

solution, but a "Pareto front" of a solution set. To accelerate the optimization progress, 5000 macro particles were used in the MOGA-II optimization, and the solutions with emittance higher than 1 mm−mrad, bunch length longer than 1.5 mm, or higher-order energy spread larger than 15 keV were discarded. The optimal solution was finally run with higher accuracy, i.e., 100000 particles.

RESULT AND DISCUSSION

The evolution of electron beam parameters for the optimal case can be found in Fig. 2. We observed significant increase of projected emittance in the DC gap and 1.5-cell cavity, which is due to the slice emittance mismatch caused by space charge effect and time-dependent rf kick. This increase of projected emitttance, however, is largely compensated by the solenoids and eventually the emittance gets frozen in the injection linac. The normalized transverse rms emittance at the exit of the injector beamline is 0.49 mm−mrad, as shown in Fig. 2(a). In this case, the initial thermal emittance (0.43 mm−mrad) is 88% of the projected emittance, which indicates the effectiveness of emittance compensation.

At the exit of the injector beamline, the bunch length is compressed to 1.05 mm and the higher-order energy spread is within 5 keV (rms), as shown in Fig. 2(b) and Fig. 2(c). A detailed investigation of the electron beam evolution shows that the buncher (the 2-cell cavity and third-harmonic cavity) has little influence on the projected emittance, as can be inferred from Fig. 2(a).

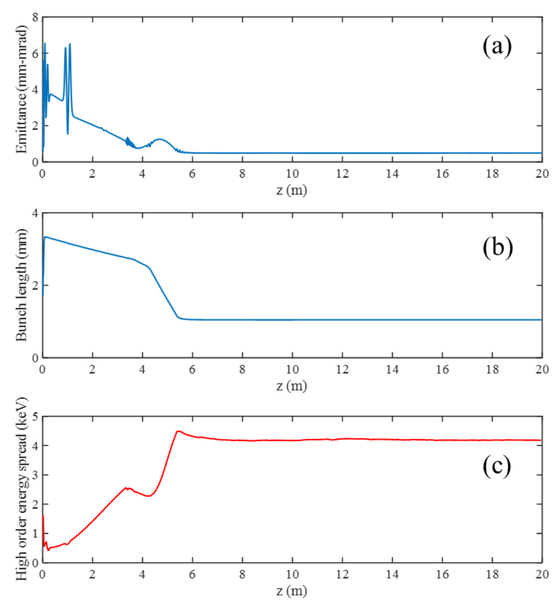

Figure 2: The evolution of electron beam parameters. (a) Emittance. (b) Bunch length. (c) Higher-order energy spread.

Fig. 3 presents more details about the electron beam distribution at the injector beamline exit. As shown in Fig. 3(a), the linear and quadratic correlation energy spread are eliminated by the injection linac and linearizer. The remaining higher-order energy spread is 4.4 keV, while the peak current is 11.3 A. Fig. 3(c) plots the slice energy spread, from which one can see that most slices have an energy spread $\lesssim$ 1keV. The tail part of the beam (on the left side), albeit with larger slice energy spread, has much lower local current. Fig. 3(d) plots the slice emittance and mismatch parameter. As shown in the figure, for most slices, the emittance is under

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0.5 mm−mrad and the mismatch parameter is close to the perfectly matched value of 1.

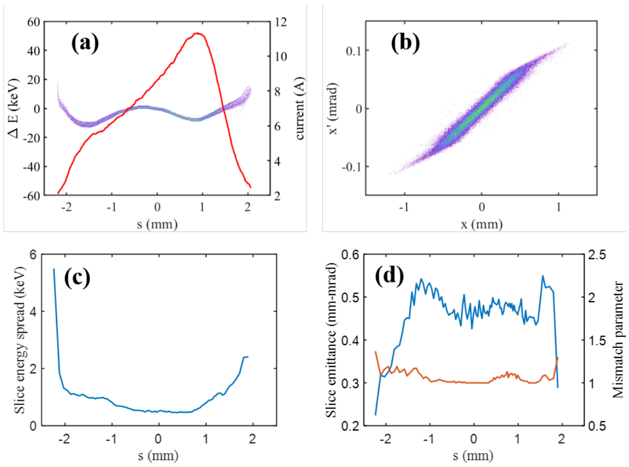

Figure 3: Electron beam distribution at the exit of the injector beamline. (a) Longitudinal phase space and current profile. (b) Transverse phase space. (c) Slice energy spread. (d) Slice emittance and mismatch parameter.

As mentioned earlier, the harmonic cavity in the buncher was introduced to improve the bunching performance. Similar configuration has been used in some recent work [7]. To illustrate its effect, we turned off the harmonic cavity and run the simulation again. The results are shown in Fig. 4. We can find the bunch length almost doubles (increases to 1.9 mm), although the peak current only decreases a little to 9.6 A. This is attributed to the inadequate bunching of the electron beam, as indicated by the long tail in Fig. 4(c). The effect of harmonic cavity will be further studied, and the cavity position, phase, and amplitude may be adjusted for better bunching performance.

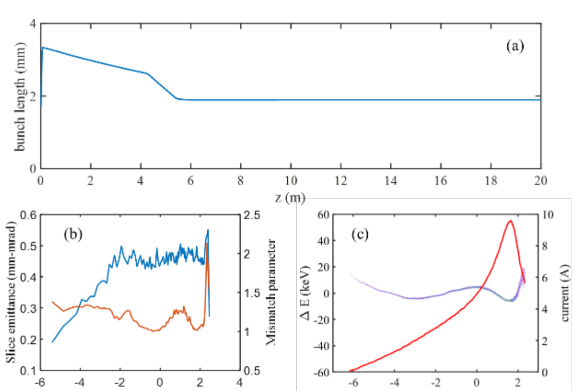

Figure 4: Simulation result of the optimal solution with the harmonic cavity turned off. (a) The evolution of bunch length. (b) Slice emittance and mismatch parameter. (c) Longitudinal phase space and current profile.

We finally investigated the same optimal solution with thermal emittance coefficient reduced to 0.6 and 0.8 mm−mrad/mm. The emittances at the exit of the injector beamline are 0.34 and 0.41 mm−mrad, respectively. The longitudinal distribution almost remains unchanged for all these cases (Fig. 5).

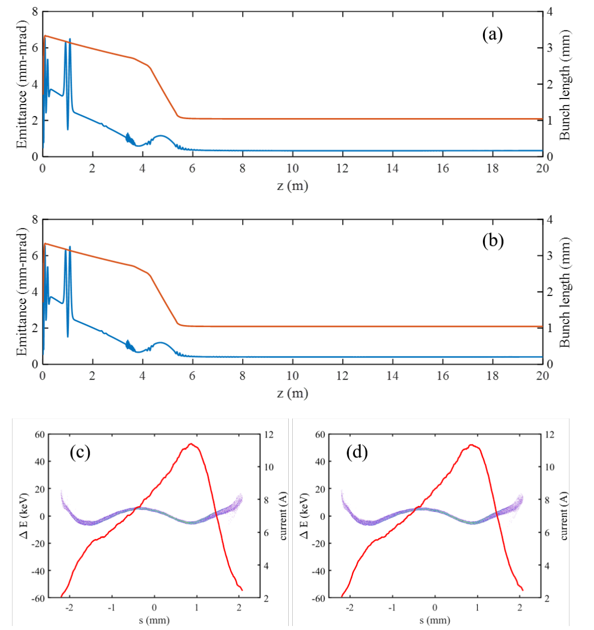

Figure 5: Simulation results of the optimal solution with thermal emittance coefficient of 0.6 and 0.8 mm−mrad/mm. (a-b) Emittance and bunch length. (c-d) Longitudinal phase space and current profile. (a) and (c): 0.6 mm−mrad/mm; (b) and (d): 0.8 mm−mrad/mm.

CONCLUSION

The performance of DC-SRF-II injector with Cs_2Te cathode has been investigated as an electron source for CW XFEL. An injector beamline was designed and optimized. The simulation shows that electron beams with a normalized rms emittance below 0.5 mm-mrad, bunch length ~ 1 mm (rms), peak current of 11.3 A, and higher-order energy spread less than 5 keV (rms) can be obtained at the bunch charge of 100 pC and electron energy of 100 MeV.

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