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BEAM DYNAMICS STUDY OF A PHOTO-INJECTOR AT WUHAN LIGHT SOURCE

Ze-Yi Dai, Yuan-Cun Nie†, Zi Hui, Jian-Hua Zhong, Lan-Xin Liu, Zi-Shuo Liu, Jia-Bao Guan, Wei-Wei Zhou, Kai-Shang Zhou, Ji-Ke Wang, Yuan Chen, Ye Zou, Hao-Hu Li, Jian-Hua He††
The Institute for Advanced Studies, Wuhan University, Wuhan 430072, China

Abstract

A photo-injector is under development at Wuhan Light Source (WHLS) to provide beams for the 1.5 GeV storage ring proposed as a fourth-generation synchrotron radiation light source and a future free electron laser (FEL) facility. The photo-injector and the following LINAC will be able to produce electron beams with low emittance (<2 mm·mrad), high bunch charge (~1 nC), small energy spread (<0.5%), and short bunch length, which meet the requirements of the ring injection and the FEL operation simultaneously. The injector boosts the bunch energy to 100 MeV, which is mainly composed of a photocathode RF gun working at 2998 MHz, two solenoid coils for emittance compensation, and two 3-meter-long 2998 MHz traveling-wave (TW) accelerator units. Beam dynamics optimization of the photo-injector is presented in detail, which has been performed with multi-objective genetic algorithm (MOGA) combining theoretical analysis and ASTRA code. After optimization, the 95% projected transverse emittance has reached as low as 0.45 mm·mrad with an RMS bunch length of about 1.0 mm at a bunch charge of 1 nC. Such emittance is close to the intrinsic thermal emittance at the photocathode, implying that there is almost no emittance growth during beam transmission.

INTRODUCTION

Including the 4th generation diffraction-limited storage rings (DLSR) and FEL, WHLS is proposed to be built in Wuhan, Hubei Province of China. It is planned to construct a 1.5 GeV low-energy storage ring with emittance less than 230 pm·rad in stage I. A photo-injector is an ideal candidate to guarantee performance of the accelerator, which can provide high brightness electron beams at the source.

The photo-injector system at WHLS boosts the bunch energy to 100 MeV with high bunch charge and low emittance, which consists of a 1.6-cell normal conducting RF (NCRF) gun followed by two 3 m-long S-band accelerator units, and two solenoids placed at the exit of the gun and around the first accelerator unit, respectively. Such a design can produce electron beams with high bunch charge and low emittance, which is widely adopted in the similar facilities, such as MAX IV, HALF, LCLS, Pal-FEL, Swiss-FEL, etc. [1-5].

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† email address：nieyuancun@whu.edu.cn
†† email address：hejianhua@whu.edu.cn

BEAM DYNAMICS OPTIMIZATION WITH ASTRA CODE

Layout of the injector system is shown in Fig.1. The projected transverse emittance is determined by a large number of parameters, including transverse and longitudinal distribution of the driving laser pulse, field gradient and phase of the RF gun, magnetic field strength and profile excited by the solenoid coils, field gradient and phase of the S-band TW accelerator units, and locations of these hardwares. To find the global optimal solution, the multi-objective genetic algorithm (MOGA) combined with ASTRA code can be used [6,7]. However, before combination of the two tools, it is necessary to narrow down the scanning range of each parameter to accelerate convergence.

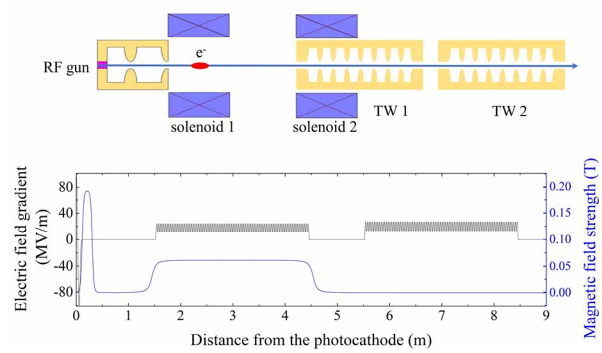

Figure 1: Layout of the photo-injector at WHLS.

The driving laser with temporal flat-top distribution and transversely truncated Gaussian distribution can linearize the space-charge effect [8]. According to experience, flat-top temporal distribution with a full-width-at-half-magnitude (FWHM) pulse length of around 10 ps and transversely about 1 sigma truncation of Gaussian distribution are selected in our simulation. The RMS transverse beam size can be calculated by $Q = \pi r^2 \varepsilon E$, where E is the electric field during photoemission, r is the beam radius, ε is permittivity of vacuum, and Q is initial bunch charge. To obtain a bunch charge of 1 nC or even higher, Cs_2Te semiconductor photocathodes are preferred, which are widely used in photo-injectors with the advantage of high quantum efficiency (QE) and moderate lifetime. Operating RF field gradient in the gun should be as low as possible to prolong the photocathode lifetime. On the other hand, higher field gradient in the gun is profit for improving beam emittance. To make a compromise, the gradient was set to 100 MV/m. The intrinsic thermal emittance at the photocathode was set to 0.9 mm·mrad/mm.

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To determine the range of the RF gun phase during optimization process of MOGA, the phase from -180ºto 180º has been scanned with a step of 1ºin ASTRA. As implied in Fig.2, to have the output beam energy higher than 4 MeV and bunch charge of 1 nC at the same time, the corresponding phase range should be from -20ºto 30º.

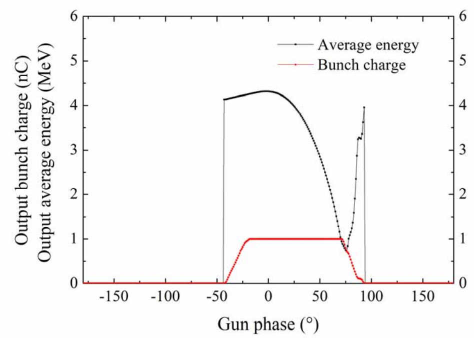

Figure 2: Output bunch charge and beam energy varying with the RF gun phase.

Solenoid 1 focuses the beam transversely and aligns the slice distribution of the bunch in the transverse phase space to compensate for the emittance growth owing to linear space charge forces. As shown in Fig. 3, effects of the magnetic field strength on the transverse emittance and beam envelope have been simulated. It can be seen that the beam envelope keeps increasing along the beamline without a beam waist when the magnetic field strength is 0.17 T. To match the beam to the first accelerator unit, the emittance compensation is needed and the beam envelope should be at a waist when injecting into the LINAC [9]. As the magnetic field strength increases, the beam waist moves closer to the gun with a smaller beam size. To make enough space for installation of beam diagnostics and vacuum systems, the distance between the entrance of TW1 and the photocathode surface need to be more than 1.2 m. As a result, magnetic field strength of solenoid 1 ranges from 0.17 T to 0.2 T in the following simulation of MOGA.

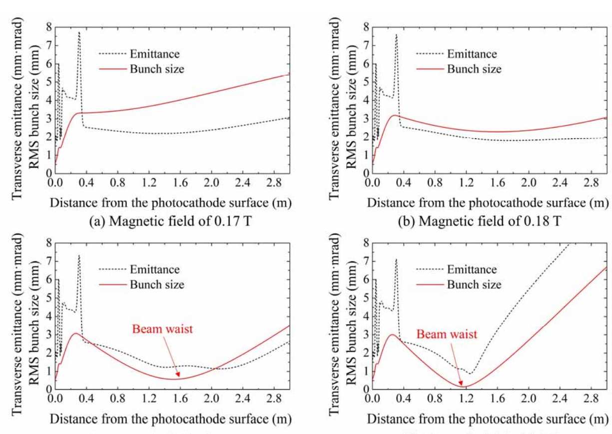

Figure 3: Transverse emittances and bunch sizes at various magnetic fields of Solenoid 1.

The matching waist size is determined by balancing the RF transverse force in the LINAC and the space charge force, which meets the relation of:

$$\sigma_{linac} = \frac{mc^2}{eE_{linac}} \sqrt{\frac{I}{2I_A \gamma}} . \quad (1)$$

where σ_{linac} is the RMS transverse beam size at the entrance of the LINAC, E_{linac} is the peak accelerating field in the LINAC, γ is the relativity factor, mc^2 is the rest energy of electron, and I_A=17 kA. The average beam energy is about 4.3 MeV. To control the RMS beam size within 1 mm, the peak accelerating field larger than 9 MV/m will be required. Thus, the minimum peak accelerating field of TW1 is set to 9 MV/m, while the maximum value is limited to be 25 MV/m according to experience.

BEAM DYNAMICS OPTIMIZATION BASED ON MOGA

Based on above discussions, the variables in the beam dynamics optimization based on MOGA are listed in Table 1. The population size was set to 100, and the number of generations for each optimization was set to 500. Progression of the Pareto front was monitored every 10 generations after initially 100. When there was no significant improvement of the Pareto front found, the optimization was stopped automatically. To compromise between running time and accuracy, 10k macro particles were used in beam dynamics simulations.

Table 1: Main Parameters for Beam Dynamics Optimization

Decision variables	**Ranges**
Laser transverse size [a]: σ_{inp}	0.5~2.0mm
Laser transverse cut [a]: C_{Cut}	0.5~2.0
Laser temporal FWHM	5 ~ 20 ps
Gun phase	-20º ~ 30º
TW1 start position [b]	1.2~2 m
TW1 field gradient	9~25 MV/m
Solenoid1 field	0.17~0.2 T
Solenoid2 field	0.01~0.2 T
Objectives	**Goals**
100% projected emittance	Minimize
RMS bunch length	Minimize
Constraints	**Ranges**
Bunch charge	1 nC
Output energy spread	< 0.5%

[a] Laser transverse truncated 2D-Gaussian distribution:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma_{inp}} \exp(-\frac{x^2}{2\sigma_{inp}^2}) \text{ for } |x| \le C_{Cut}\sigma_{inp}$$

[b] Distance from the surface of the photocathode

The obtained Pareto front composed of non-dominant solutions is shown in Fig. 4, which demonstrates the relationship between the 100% projected emittance and RMS bunch length. It indicates that selecting a lower

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emittance is usually at the cost of allowing a longer bunch length.

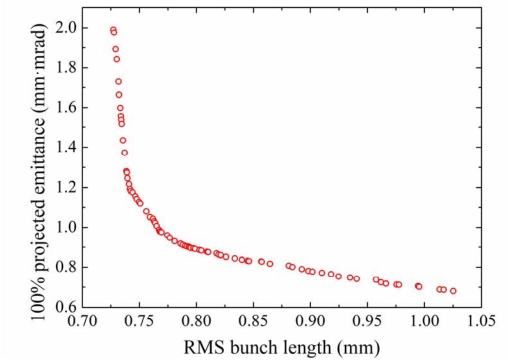

Figure 4: Multi-objective optimization results.

In our design, the minimum 100% projected emittance was set as the working points, and 100k macro particles were simulated to improve accuracy. In Fig. 5, the 100% projected emittance is 0.61 mm·mrad with an RMS bunch length of 1.03 mm. As shown in Fig. 6, the 95% normalized transverse emittance is 0.45 mm·mrad, which is equal to the intrinsic thermal emittance, with a peak current of about 100 A. The corresponding optimization results are shown in Table 2.

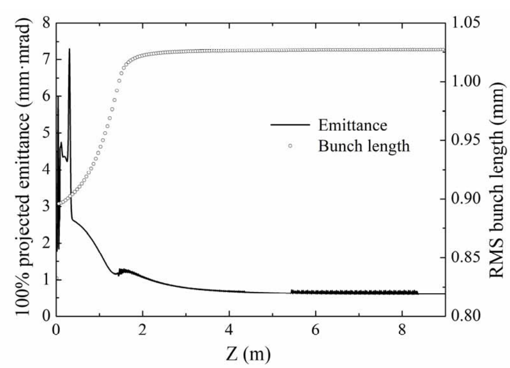

Figure 5: Evolution of 100% projected emittance and RMS bunch length along the photoinjector.

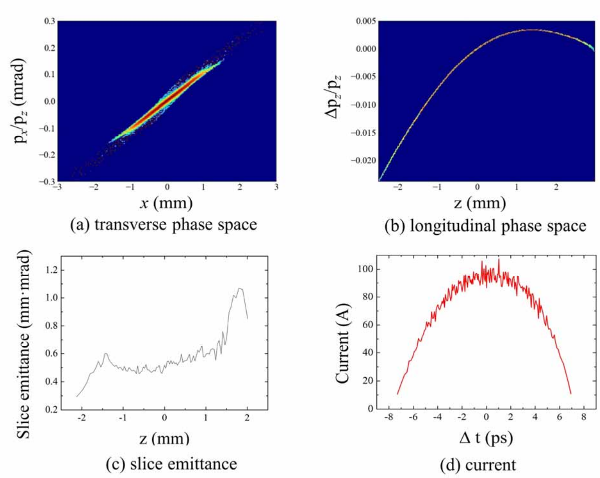

Figure 6: Beam dynamics optimization results at 1 nC.

Table 2: Output Bunch Parameters

Parameters	Values
Energy	100.8 MeV
Energy spread	414 keV
RMS bunch length	1.027 mm
100% projected emittance	0.61 mm·mrad
95% projected emittance	0.45 mm·mrad

CONCLUSION

In this paper, physics design of the photo-injector at WHLS has been presented in detail. By combining MOGA and ASTRA, the accelerating and focusing components have been optimized globally. A 95% normalized projected transverse emittance as low as 0.45 mm·mrad has been obtained at a bunch charge of 1 nC, which is equal to the intrinsic thermal emittance at the photocathode, indicating that there is almost no emittance growth in the process of beam acceleration and transport.

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