LOW EMITTANCE INJECTOR DEVELOPMENT FOR THE PAL-XFEL PROJECT*

J.-H. Han†, J. Hong, I. Hwang, M. S. Chae, S.-J. Park, H.-S. Kang, I. S. Ko,
Pohang Accelerator Laboratory (PAL), Pohang, 790-784, Republic of Korea

Abstract

An injector for low emittance electron beam generation as well as high repetition rate and more reliable operation is under development at PAL. Here, we introduce the design of the S-band photocathode gun using a coaxial coupler for the PAL-XFEL project. The gun will be able to provide a low emittance electron beam for ultimate X-ray FEL performance. Injector beam dynamics optimization using this gun is shown. Various injector operating conditions are studied numerically.

INTRODUCTION

The Pohang Accelerator Laboratory X-ray Free electron Laser (PAL-XFEL) project [1] started in 2011. This project aims at the generation of X-ray FEL radiation in the range of 0.1 to 10 nm for users. The machine consists of a 10 GeV linear accelerator and soft and hard X-ray undulator beamlines. The accelerator will operate at a repetition rate of 60 Hz. Building construction starts in September 2012.

The PAL-XFEL baseline injector [2] was designed for satisfying the PAL-XFEL beam requirements. The baseline injector adopts the GTF gun [3, 4] developed at PAL over the last six years and two 3 m long S-band traveling-wave tubes. The injector has been installed in the Injector Test Facility (ITF) and first beam generation is foreseen in September 2012. RF conditioning of the gun cavity and accelerator tubes is being started. Numerical simulations using the baseline injector shows 0.26 mm mrad normalized transverse rms emittance at 200 pC are achievable [2]. The experimental target is 0.4 mm mrad as first phase. For emittance measurements, three quadrupole magnets and a screen will be used [5].

Transverse emittance of an electron beam has a crucial role in hard X-ray SASE FEL. For the PAL-XFEL hard X-ray case, a 50% emittance reduction will result in 30 to 50% FEL power increase as well as 20 to 50% FEL saturation length reduction depending on other parameters [6]. Even though the baseline injector will fully satisfy the PAL-XFEL beam parameter, a low emittance injector will allow better FEL performance with reduced undulator length.

The low emittance injector has two major changes compared with the baseline injector. The RF gun with a side coupler is replace with a gun with coaxial coupler. Three accelerator tubes will be used for acceleration instead of two tubes in the baseline injector. Possible future installation of the low emittance injector in the PAL-XFEL main linac will be also discussed.

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† janghui_han@postech.ac.kr

LOW EMITTANCE GUN

The PAL-XFEL low emittance gun is similar as the Diamond S-band (2.998 GHz) gun which was developed for high repetition rate operation and low emittance beam generation [7]. By adopting a coaxial RF coupler connected at the gun exit as for the DESY PITZ gun [8], the gun solenoid can be positioned at an optimum location for low emittance and cooling water channels can fully surround the gun cavity cylinder for maximizing cooling capacity and allowing uniform temperature distribution over the gun body. With an exchangeable photocathode plug, high quantum efficiency cathodes can be used for reducing drive-laser power requirement and a damaged cathode can be easily replaced with a fresh one under ultra-high vacuum. Since the PAL-XFEL gun should operate at 2.856 GHz, the Diamond gun cavity was enlarged by about 5% and cooling channel was adjusted. The first technical design is ready.

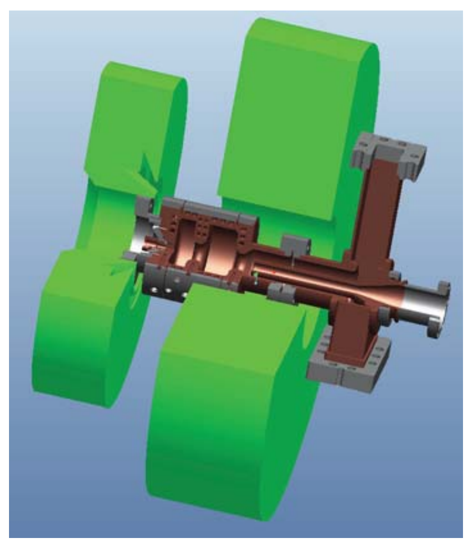

Figure 1: Low emittance gun cavity and solenoids. A cathode exchange system is connected at the rear of the gun.

In this gun design, the center of the solenoid is at 0.105 m from the cathode. For magnetic field compensation at the cathode, a bucking solenoid is placed immediate upstream of the gun.

Maximum repetition rate required for the PAL-XFEL gun is 120 Hz even considering future upgrade [1]. At the first gun design, no RF pick-up probed was included as for

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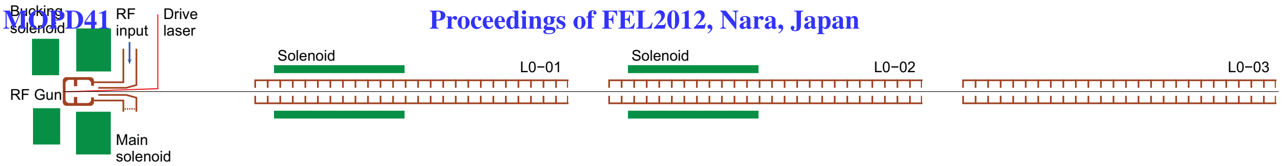

Figure 2: Layout of the low emittance injector consisting of an RF photocathode gun, focusing solenoids, and three accelerating sections.

the Diamond gun. Since the average RF power dissipation in the PAL-XFEL gun, 3 kW, is low, the cooling channel may be simplified and RF pick-up probes can be implemented. Work for a new technical design is ongoing.

INJECTOR OPTIMIZATION

The low emittance injector consists of the new gun, three 3 m long S-band constant-gradient traveling-wave structures, focusing solenoids, and a laser heater system. As discussed in the previous section, the gun main solenoid is placed at 0.105 m from the cathode, shifted upstream by about 0.1 m compared to the baseline injector. By placing the gun solenoid at that location, beam focusing by the gun solenoid is made upstream compared to the baseline injector. At this new injector design the first accelerating section is place at 1.7 m from the cathode. Focusing solenoids will be mounted at the first two accelerating sections as for the baseline injector. 200k macro particles are used for beam tracking using the ASTRA code [9] and 2M macroparticles were used for the final results.

A flat-top longitudinal laser pulse shape will be achieved by stacking Gaussian pulses as shown in Fig. 3. Transverse size of a laser pulse should be minimized in order to have a small therm emittance. In numerical simulations using the ASTRA code, 0.9 mm mrad thermal emittance per 1 mm laser pulse radius is included. The transverse profile of a laser pulse is assumed to be uniform.

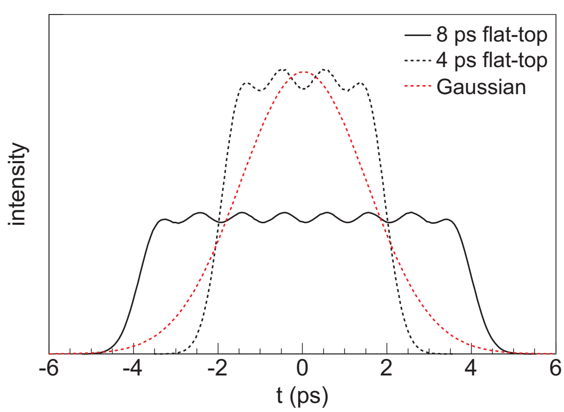

Figure 3: Longitudinal laser pulse profiles used for injector beam dynamics simulations. 8 ps flat-top is achieved by stacking 8 Gaussian pulses and 4 ps is by 4 pulses. As first phase operation, a simple 1.5 ps rms Gaussian pulse may be used.

Nominal Bunch Charge Case, 200 pC

Three operation options are studied with ASTRA simulation. The nominal operation condition uses a 8 ps flat-top laser pulse (configured with 8 Gaussian pulses) for minimum transverse emittance. A 4 ps flat-top laser pulse (with 4 Gaussian pulses) is used for short bunch generation. A Gaussian laser pulse is considered for initial operation without pulse shaping. The same injector setup is used for all the operation options except for the laser beam size and focusing solenoid field strength. The parameters of the injector and simulation results are summarized in Table 1.

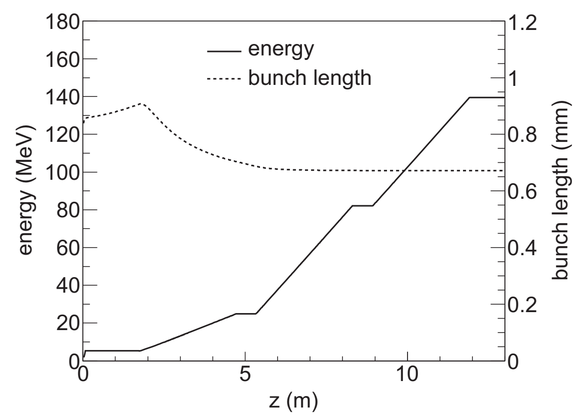

Figure 4: Beam energy and bunch length evolution for the 200 pC nominal case using a 8 ps flat-top laser pulse.

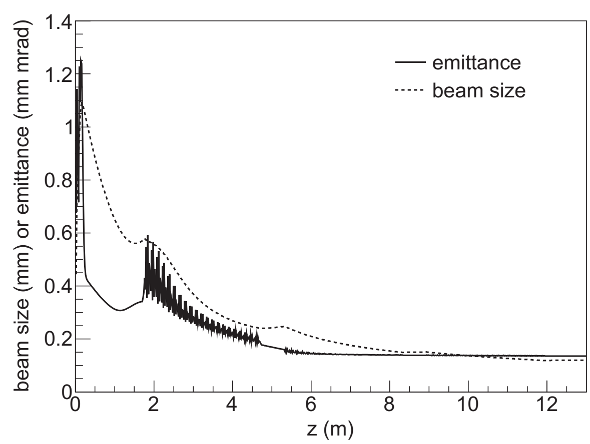

Figure 5: Beam size and normalized transverse projected emittance for the 200 pC nominal case.

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The energy and bunch length evolution of a bunch though the injector is shown in Fig. 4 for the nominal condition. The gun operates at 120 MV/m maximum field at the cathode. The launch phase of a beam is $-1°$ from the phase generating the maximum energy gain though the gun. In other words, the launch phase is $46°$ from the RF 0-crossing phase. Mild velocity bunching is applied at the first accelerating section. The gradient of the first section is relatively low (14 MV/m) to minimize beam emittance increase caused by the RF field. The second and third accelerating sections have a 20 MV/m gradient and a 16° phase for compensate the energy chirp produced by the first section. The beam size and normalized transverse emittance evolution is shown in Fig. 5.

The current profile and slice emittance of bunches for the three options are shown in Fig. 6 and 7. The op-

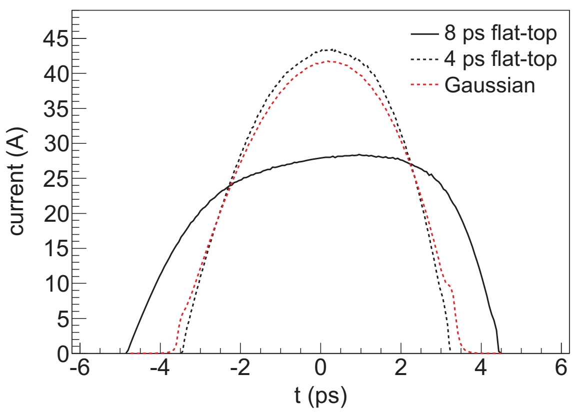

Figure 6: Current profiles of 200 pC bunches at the injector end for the three longitudinal profile options of cathode laser pulses.

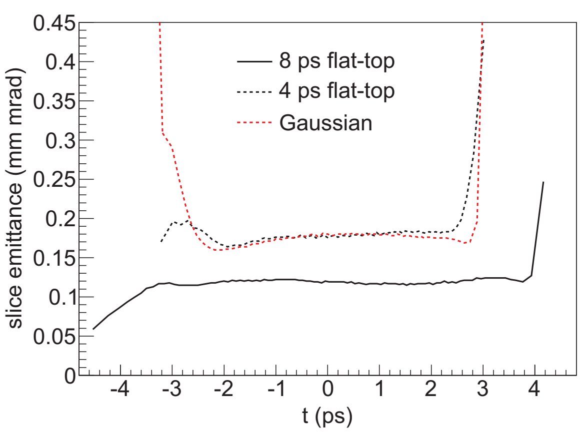

Figure 7: Normalized transverse slice emittance of 200 pC bunches at the injector end.

tion using a 8 ps laser pulse shows longer bunch length but lower transverse emittance. The options using 4 ps flat-top and Gaussian laser pulses show similar current profiles and slice emittances. However, the projected transverse emittance for the Gaussian laser pulse case is 35% larger than the case for the 4 ps flat-top (see Table 1).

Low Bunch Charge Case, 20 pC

Two operation options are studied using a 4 ps flat-top laser pulse and a Gaussian laser pulse. The same injector setup as for the 200 pC cases is used except for the laser beam size and focusing solenoid field strength. The simulated current profiles and slice emittances of 20 pC bunches are shown in Fig. 8 and 9. The current profile and slice emittance for the two options are similar, however the projected emittance for the Gaussian laser pulse case is 20% larger than the case for the 4 ps flat-top (see Table 1). The machine parameters and simulation results are summarized in Table 1.

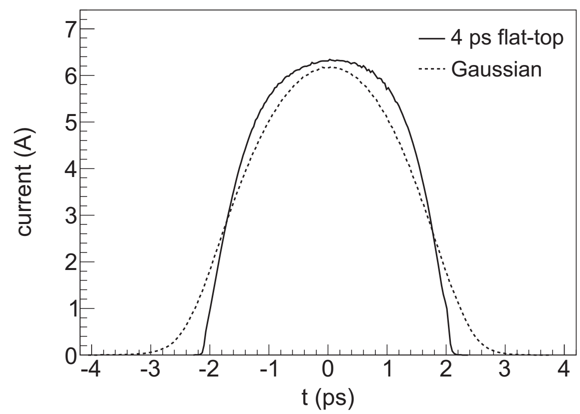

Figure 8: Current profiles of 20 pC bunches at the injector end.

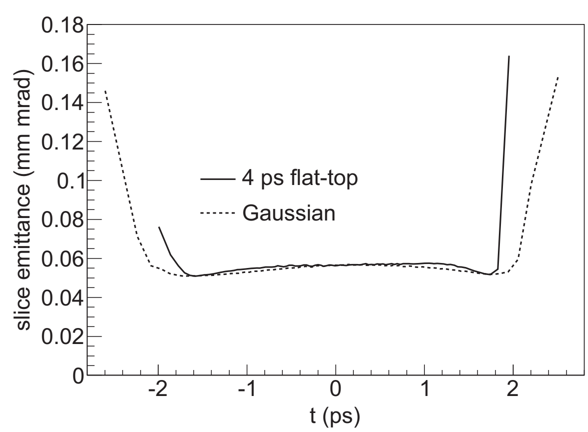

Figure 9: Normalized transverse slice emittance of 20 pC bunches at the injector end.

POSSIBLE IMPLEMENTATION TO THE PAL-XFEL MAIN LINAC

This low emittance injector has another 3 m long accelerating section compared with the baseline injector. Including vacuum connection parts, 3.6 m more space is needed.

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Table 1: Simulation Parameters of the Low Emittance Injector for Flat-top (F) and Gaussian (G) Longitudinal Cathode Laser Pulse Shapes

Bunch charge (pC)	**200**	**200**	**200**	**20**	**20**
Laser/cathode					
Length (ps)	8 fwhm (F)	4 fwhm (F)	1.5 rms (G)	4 fwhm (F)	1.5 rms (G)
Rise/fall time (ps)	0.8	0.8	-	0.8	-
Rms beam size (mm)	0.12	0.18	0.18	0.06	0.06
Thermal emittance (mm mrad)	0.108	0.162	0.162	0.054	0.054
Gun					
Peak field at cathode (MV/m)	120	120	120	120	120
Beam launch phase from 0-crosing	46°	46°	46°	46°	46°
Max field of the main solenoid (T)	0.383	0.384	0.384	0.382	0.381
Accelerating section					
Gradient of 1st section (MV/m)	14	14	14	14	14
Gradient of 2nd section (MV/m)	20	20	20	20	20
Gradient of 3rd section (MV/m)	20	20	20	20	20
Phase of 1st section from on-crest	−67°	−67°	−67°	−67°	−67°
Phase of 2nd section from on-crest	16°	16°	16°	16°	16°
Phase of 3rd section from on-crest	16°	16°	16°	16°	16°
Max field of the 1st linac solenoid (T)	0.064	0.070	0.070	0.056	0.058
Max field of the 2nd linac solenoid (T)	0.02	0.0	0.0	0.0	0.0
Electron beam, simulation					
100% rms projected emittance (mm mrad)	0.133	0.203	0.276	0.060	0.073
Slice emittance at center (mm mrad)	0.120	0.177	0.179	0.056	0.056
Fwhm bunch length (ps)	7.6	5.1	5.2	3.4	3.4
Peak current (A)	28	43	41	6.3	6.1
Mean E (MeV)	139.4	139.4	139.4	139.4	139.4

In the current design of the PAL-XFEL linac, a 5 m long space after the laser heater system is reserved for injector beam diagnostics including an RF deflector and an emittance measurement section. When the baseline injector is replaced with this low emittance injector, the diagnostic section may be simplified and the laser heater system can be shifted downstream. Since the beam energy at the injector end, 139.4 MeV, is similar as for the baseline injector, 139.1 MeV, the same laser heater setup can be used with a small tuning of the heater undulator gap.

SUMMARY AND FUTURE PLANS

The low emittance gun design and injector simulation were described. The transverse emittance of the low emittance injector is about 50% compared to that of the baseline injector. Furthermore, the low emittance gun will allow photocathodes to be replaced under ultrahigh vacuum. The gun will be thermally more stable with improved water-cooling channel.

A few operating options with 200 and 20 pC bunch charges were numerically studied with the injector. Even though the 8 ps laser pulse option shows the lowest emittance case at 200 pC, a simple short Gaussian laser pulse may be used at the first phase of injector operation. When the cathode laser system is fully commissioned, the lowest emittance option may be tried to generate a low emittance electron beam for the PAL-XFEL linac.

The gun system is under preparation to be ready by spring 2013. The first technical design of the gun is ready but further optimization including RF probes is ongoing. The gun system is planed to be tested at the additional beamline in the ITF tunnel at the first phase.

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