OPTIMIZATION AND SENSITIVITY STUDIES FOR PAL FEL INJECTOR

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Abstract

Pohang Accelerator Laboratory (PAL) is preparing a 0.1 nm free electron laser based on Self-Amplified Spontaneous Emission (SASE). S-band rf linear accelerator will produce a 10 GeV electron beam and in-vacuum undulators of 5 mm gap make output radiation power of 5 GW. To determine basic design parameters, start-to-end tracking simulations are performing by the tracking codes. We present simulation result of injector part by PARMELA. It consists of electron gun, solenoids, two 3 m linac and quadrupoles. The photoinjector produces 10 ps long electron bunches of 1 nC with a normalized transverse emittance of less than 1 mm mrad at 135 MeV. Sensitivity studies of laser pulse, solenoid and linac are presented also.

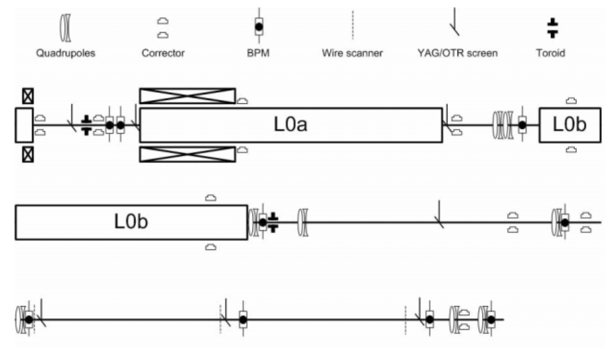


Figure 1: Schematic layout of the injector including the rf gun, the accelerating cavities and the diagnostic devices.

INTRODUCTION

0.1 nm Self-Amplified Spontaneous Emission (SASE) Free Electron Laser (FEL) at Pohang Accelerator Laboratory (PAL) plans to employ in-vacuum undulators of 5mm gap in conjunction with an S-band rf linear accelerator to produce a 10 GeV electron beam. When a 1 nC electron beam with 1.1 mm mrad normalized slice emittance and 0.015% relative slice energy spread enters the undulator, output radiation power of 5 GW is expected in 92 m saturation length. Start-to-end tracking simulations are performing to determine the basic design parameters and to verify the performance of the PAL FEL. The simulation study can be separated into three parts. PARMELA simulates the injector part including the rf gun and the initial accelerating cavities [1, 2, 3, 4]. The main linac is studied by SAD and ELEGANT. The final performance of the undulator is investigated by GENESIS. The 6-dimensional electron distribution of the previous stage is used for the initial state of the next simulation study.

The goal of the injector for the PAL FEL is to deliver to the main linac a single 135 MeV electron bunch of charge 1 nC, length 10 ps and normalized transverse emittance 1 mm mrad. In this paper, we present the design and the sensitivity simulation results by PARMELA for the PAL FEL.

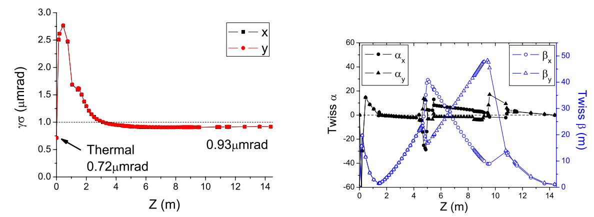
INJECTOR DESIGN

The basic structure is similar to the injector part of the Linac Coherent Light Source (LCLS) [1, 2, 3, 5]. Because PAL FEL is straight structure, the bending magnet is excluded and the parameters of the main components are retuned for PAL FEL. The injector consists of a rf gun, two S-band rf cavities and straight sections for the diagnositic devices as shown as Figure 1. The electrons are created at the 1.6-cell S-band rf gun surrounded by a solenoid at the gun exit[4, 6, 7]. A corrector magnet and some diagnostic devices like as BPM and YAG/OTR screen are placed in a drift. Two standard SLAC 3m traveling wave accelerating cavities provide energy boost up to 135 MeV. Eight quadrupole sets control the beam size and the twiss parameters are tuned to produce a round beam at the exit.

Simulated Properties

The laser pulse distribution on the cathode of an rf photoinjector is important in a space-charge dominated beam. In PAL FEL, the temporal shape of the electron pulse which is same as the laser pulse is determined as a flat-top because it is better than a gaussian distribution in an emittance compensating process by a solenoid located the gun exit[4]. A uniform distribution filled in an ellipsoid can be better than a flat-top shape but it may be harder to stabilize because its pulse generation scheme is more complex[8, 9, 10, 11]. The flat-top temporal profile is enough to produce a desirable electron bunch in PAL FEL. The beam radius is set to 1.2 mm and corresponding initial emittance is chosen as 0.72 μmrad which is based on a experiment result 0.6 μmrad per 1 mm beam radius[3, 12, 13].

As shown in Figure 2(a), the normalized transverse emittance is increased by the space-charge force in the rf gun and is compensated by a solenoid located at the gun exit. The second solenoid located at the entrance of the first accelerating cavity is used for a minor correction. The first accelerating cavity provides acceleration of 19.8 MV/m during 3 m and second one 24.0 MV/m. The main parameters are listed in Table 1. The laser phase to rf gun is selected to produce the minimum emittance and the cavity phases are chosen for minimize the energy spread. The



(a) (b)

Figure 2: The time evolution of the normalized transverse emittance (a) and the twiss parameters along the longitudinal coordinate (b).

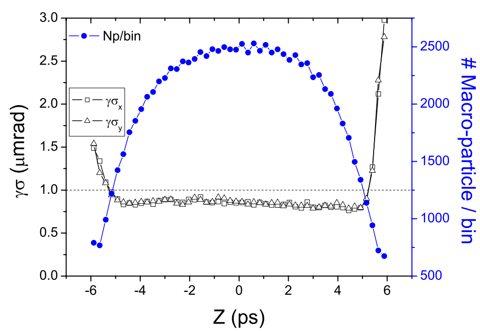


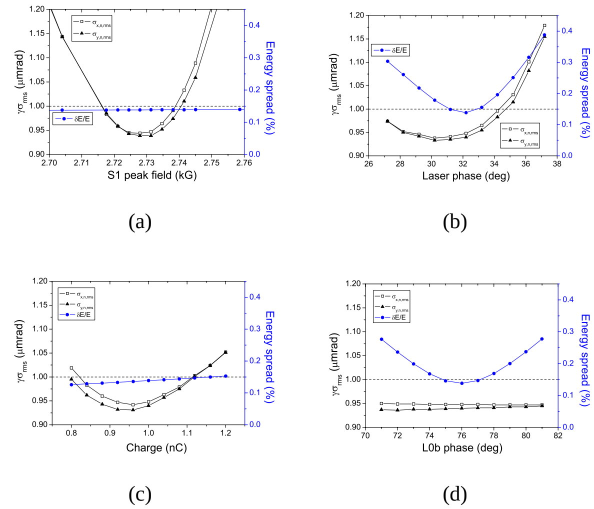
Figure 3: The slice emittance at the end of the injector part. The transverse emittance of 90% core is about 0.8 μm rad.

twiss parameters are shown in Figure 2(b). Two quadrupole sets located the exit of the cavities focus the electron beam and the other quadrupoles are used to make a round beam. The twiss parameter should be matched with main linac part.

Because the temporal edge and the core of electron bunch feel different space-charge force, their distributions in the phase-space evolute in different way. It leads to the emittance growth even if the beam has zero emittance initially. The solenoidal field can compensate this emittance growth by appling different kick to each part. It works well for ideal case of the linear space-charge force and the temporal square bunch. If the temporal edge is not step function, this emittance compensation process does not work ideally. The halo is formed at the edge and the slice emittance of the edge is greater than core part[3]. Figure 3 shows the slice emittance at the end of the injector part. The 80% of the equally spaced slices contain 90% charge of full bunch and have 0.8 μm rad transverse emittance. The slice emittance is important because the edges do not contribute to lasing in a undulator.

Sensitivities

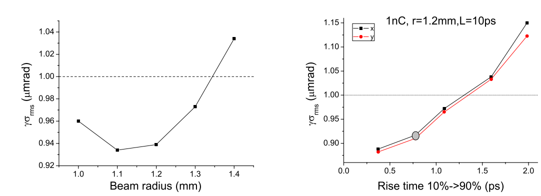
A sensitivity study of the major parameter was performed to help the tolerance determination. The sensitivity of the phases defines levels of jitter on the power supply



(a) (b)

(c) (d)

Figure 4: The normalized transverse emittance and the energy spread as a function of a single parameter. The others are fixed at the optimized value.



(a) (b)

Figure 5: The normalized transverse emittance as a function of beam radius or rise-time. The solenoid strength is optimized for each beam shape.

for the rf gun and the accelerating cavities. The sensitivity of the solenoid strength gives a clue for the regulation limits for the power supply. The beam charge and the laser phase are related to the stability requirements of the laser system. A single parameter like as the charge, the solenoid strength and the phases, is varied around the optimized value[3, 14]. The error of the solenoid strength is most sensitive and makes no effect on the energy spread as shown in Figure 4(a). The laser phase jitter has larger effect on the energy spread than the emittance as shown in Figure 4(b). The charge of 1 nC is a requirement of the PAL FEL injector. Due to the mismatch of the emittance compensation setting, the deviation of the bunch charge leads to the emittance growth as Figure 4(c). As the beam approaches the accelerating cavity, the compensation of the emittance is almost done, the phase jitter of the accelerating cavity affects the energy spread only as shown in Figure 4(d). 5% growth for the emittance and 10% for the energy spread are chosen as the criterions to summarize the sensitivity listed in Table 1. In the case of the laser radius and the rise-time at the temporal edge, the solenoidal field is optimized for each case. As shown in Figure 5(a), the optimal beam ra-

Table 1: Sensitivity summary of 1 nC case.

Parameter	design value	$\gamma\sigma$ +5%	δE/E +10%
Charge Q	1nC	+10%	+20%
Solenoid peak strength $S1$	2.731kG	+2.7%	-
Laser phase ϕ_0	32.2^o	$\pm 2^o$	$\pm 1.1^o$
1st cavity phase ϕ_{L0a}	161.3^o	-	$\pm 1.5^o$
2nd cavity phase ϕ_{L0b}	76^o	-	$\pm 1.3^o$
laser radius r_c	1.2mm	+10%	-20%
laser rise-time τ_{rise}	0.72ps	1.3ps	-

Table 2: Sensitivity summary of 0.2 nC case.

Parameter	design value	$\gamma\sigma$ +5%	δE/E +10%
Charge Q	0.2nC	+8%	+18%
Solenoid peak strength $S1$	2.752kG	+3.2%	-
Laser phase ϕ_0	32.2^o	$\pm 5^o$	$\pm 0.5^o$
1st cavity phase ϕ_{L0a}	161.34^o	-	$\pm 1^o$
2nd cavity phase ϕ_{L0b}	76.5^o	-	$\pm 0.7^o$
laser radius r_c	0.6mm	+20%	-17%
laser rise-time τ_{rise}	0.36ps	0.8ps	-

dius is 1.1-1.2 mm. The sharper edge is better for the emittance as shown in Figure 5(b). 0.7 ps rise-time is chosen by considering the technical problems to produce sharp edge beam. The tolerance will be determined by this sensitivity information and the technical limitations.

LOW CHARGE OPTION

Another option for PAL FEL is considering to reduce the saturation length of the undulator output power by lowering the charge and the length of the electron bunch. Due to the lower charge, the smaller emittance can be achieved with the smaller electron beam[15]. The injector parameters are re-optimized and the sensitivity study is performed as listed in Table 2. The charge, the beam radius and the length are halved. Consequently, the initial emittance is halved also and the final emittance is obtained as 0.46 μm rad. The energy spread is reduced from 0.14% to 0.05% due to shorter length and more sensitive to the phase jitters of the accelerating cavities due to smaller energy spread. The solenoid strength is similar to 1 nC case because the smaller size cancels the lower charge effect. The emittance and the energy spread are less sensitive to the laser radius but more sensitive to the rise-time with optimizing the solenoid strength.

SUMMARY

The injector design for PAL FEL presented to produce 10ps long electron bunches of 1 nC with a normalized transverse emittance of 0.93 μm rad at 135 MeV. The sensitivity study was performed to help to determine the tolerance. Additional option for another FEL operation is optimized as 5ps length of 0.2 nC with an emittance of 0.46 μm rad at same energy. Its sensitivity was investigated also.

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