OPTIONS FOR PAL-XFEL INJECTOR OPERATION *

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Abstract

The present design of the PAL-XFEL injector assumes a 120 MV/m peak field at the cathode and a flat-top longitudinal drive-laser profile. As accelerating field in the gun decreases and laser shape becomes imperfect, beam quality degradation may take place. On the other hand, by reducing the accelerating field in the gun and by relaxing the drive-laser shaping requirement, the stability of injector operation can be increased. We study various options for operating conditions of the injector with relaxed RF field and drive-laser parameters.

INTRODUCTION

Pohang Accelerator Laboratory X-ray Free Electron Laser, PAL-XFEL [1, 2], will be benefited with a low transverse emittance for the generation of 0.1 nm x-ray FEL radiation. For the baseline design a 0.4 mm mmrad beam was assumed, which will generate a 17 GW FEL with a 10 GeV electron beam [4]. 0.06 nm FEL generation which is pursued as a next goal of PAL-XFEL, will need 117 m undulator length for a 7 GW FEL generation. The required undulator length for 0.01 nm radiation is close to the total undulator length to be installed. If we take account the wakefield and alignment error of quadrupoles, we may need longer undulator to achieve FEL saturation. In addition, such a level of FEL power at 0.06 nm may be insufficient to user operation.

If we can reduce the emittance from 0.4 to 0.2 mm mrad, we will be able to generate a 18.5 GW FEL power at 0.06 nm with 77 m long undulator [4]. It will allow PAL-XFEL to provide a powerful FEL radiation to users at 0.06 nm FEL wavelength or beyond.

To achieve a low projected transverse emittance, a flat-top longitudinal laser profile is used for the generation of an electron bunch at the gun. Maintaining such profile may however be hard during FEL user operation. A Gaussian laser profile may be easily achievable compared to a flat-top profile and the simpler shape may be kept stable during routine operation.

During FEL user operation, any RF breakdown must be prohibited. Since the gun requires a high RF field to achieve a low emittance, the gun section is a possible RF breakdown point. As an option to increase the reliability of PAL-XFEL operation, a low RF field at the gun may be considered. In this paper, we discuss alternative options to use a low emittance injector, a Gaussian laser profile, and low RF fields at the cathode. For numerical optimization, the ASTRA code [5] with several hundreds of thousand macroparticles was used. For the confirmation of the numerical calculations, 2M macropaticles were tracked.

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LOW EMITTANCE INJECTOR

The low emittance gun adopts a coaxial RF power coupler connected to the beam exit port of the gun cavity. The coaxial coupler allows a perfect RF symmetry in the gun cavity, a maximum water-cooling capacity, and an ideal gun solenoid position for low emittance beam generation [3]. Three 3 m traveling-wave accelerating columns follow the gun. The entrance of the first columns is at 1.9 m from the cathode. This location was optimized for the beam matching. The second and third columns start at 5.5 m and 9.1 m respectively, although the positions are not critical for the beam dynamics. The first two columns have focusing solenoids for the emittance compensation and Twiss function control (Fig. 1). There is no quadrupole magnet in the injector. More details on the low emittance injector layout can be found in [6].

A gun with the new design was fabricated recently. A local company machined the parts using 1st class oxygen free copper. The cleaning and brazing were done at PAL. RF tuning was performed before the final brazing. The resonance frequency and the field balance between the first and second cells were measured as 2856.1 MHz and 1.0 respectively. The mode separation between the pi and zero modes was 20.3 MHz, which is well matched to the numerical design. Gun commissioning is foreseen to start late autumn 2013 in an extra gun test beamline in ITF..

FLAT-TOP LASER PROFILE

Flat-top longitudinal laser profile is more efficient than Gaussian one for keeping all the slices in a bunch overlapped each other. When a 120 MV/m cathode field is applied, as low as a 0.12 mm mrad projected transverse emittance will be achieved (Table 1). A drive laser spot size of 0.12 mm was used, which minimizes the thermal emittance to 0.11 mm mrad. A thermal emittance of 0.9 mm mrad per 1 mm initial beam size (that is the laser beam size) was included in ASTRA simulations. The slice emittance at the central slices of a bunch is about 0.11 mm mrad, close to the lowest achievable limit defined by the thermal emittance.

A 14 MV/m gradient was used for the first accelerating column. Since the initial transverse beam size was minimized at the gun for a low thermal emittance, bunch length increases while transporting downstream. A mild velocity bunching with $-64°$ from on-crest phase was applied

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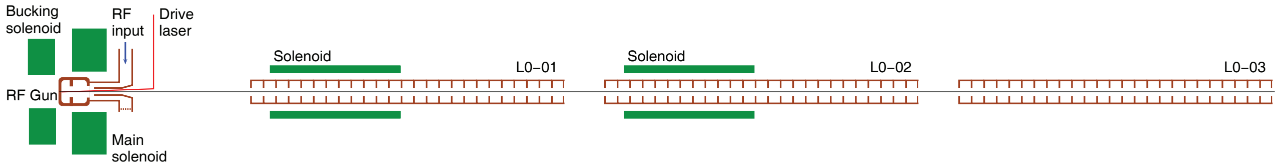

Figure 1: Layout of the low emittance injector consisting of an RF photocathode gun, focusing solenoids, and three accelerating sections.

to suppress the bunch length increase. A 19 MV/m was used for the second and third columns so that the beam energy becomes 135 MeV at the injector end. The gradient for the second and third columns was chose so that the two columns can be fed from one 80 MW RF station. A 17° from on-cres was applied to the second and third columns to remove the energy chirp at the injector end. Immediate downstream of the injector, a laser heater will be located.

In the laser heater, a heater undulator is located between the second and third bending magnets in the chicane. If the energy chirp is remained in the heater undulator, the bunch is horizontally elongated and the heater laser does not overlap with the beam. Depending on laser heater operation option, energy chirp may be remained. Using the laser heater operation scheme proposed by Dohlus [7] where the heater laser position is off-centered vertically, a bunch with an energy chirp can be effectively heated as well. When this laser heater operation option is applied, the phase of the second and third columns can be chose to be near on-crest.

GAUSSIAN LASER PROFILE

Even though a flat-top laser profile is superior to a Gaussian profile for the generation of low emittance beam, a flat- top profile may be difficult to maintain for stable operation during FEL user service. Effort is being paid to develop skills to make and operate a flat-top profile at the PAL-XFEL ITF, however we discuss here back-up options using a Gaussian profile.

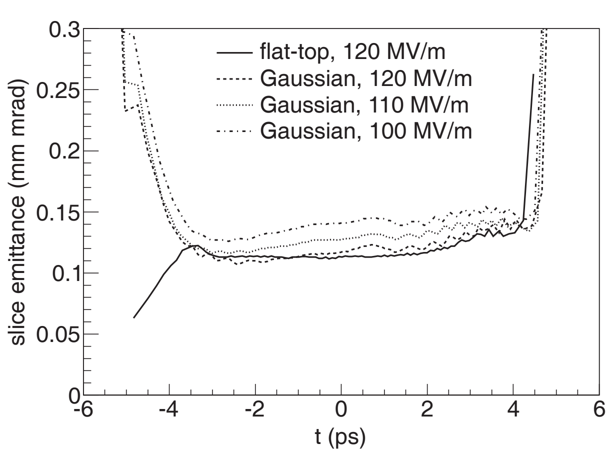

Figure 2: Slice emittance at the injector end for operation conditions using different longitudinal drive-laser profile and RF field at the cathode.

An electron beam was generated with a Gaussian longitudinal laser profile and the same injector layout was used as for the simulation in the previous section. The projected emittance at the injector end rose over 0.2 mm mrad but the slice emittance at the central slices was kept as nearly the same level as for the flat-top laser profile case (Fig. 2). At the head and tail slices, the slice emittance is large however the head and tail parts do no contribute to the FEL process. The simulation parameters are summarized in Table 1.

LOW RF FIELD AT THE GUN

At the PAL-XFEL Injector Test Facility (ITF), the gun is operating at about 120 MV/m peak field at the cathode. RF breakdown takes place a few times per week at the gun and related RF components such as RF window. This breakdown rate is not a critical problem for the test machine. Since PAL-XFEL will be a FEL user machine, such breakdown must be prohibited.

By applying a lower RF field at the gun, dark current emission at the gun can be reduced. In addition, reduced RF power at the gun section will increase the machine stability. On the contrary, a low accelerating field at the gun will not efficiently suppress the emittance rise caused by the space charge. In this section, we study options to use lower RF field at the gun as well as a Gaussian laser profile.

When the peak field at the cathode is decreased to 110 MV/m, a larger drive laser spot size of 0.12 mm (rms) had to be used in order to relax the space charge during the beam emission at the cathode. The injector parameters were the same as used for the 120 MV/m case except for the first accelerating column position. The first column was positioned at 1.75 m from the cathode instead of 1.9 m. This optimum position was found considering the beam matching at the column and bunch length at the injector end. When the original column position, 1.9 m, is used, about 5% emittance increase was calculated compared to the new column position. The slice emittance at the central slices rose to about 0.13 mm mrad, which is still much below 0.2 mm mrad. The projected emittance was reduced compared to the 120 MV/m case. This results from better slice ellipse alignment. The peak current was really the same as for the 120 MV/m case.

Another case when the peak field is further reduced to 100 MV/m was studied. The rms laser spot size was increased to 0.13 mm. The first accelerating column was positioned at 1.6 m. The central slice emittance was about

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Table 1: Simulation parameters of the low emittance injector for flat-top (F) and Gaussian (G) longitudinal drive-laser profiles.

Bunch charge (pC)	**200**	**200**	**200**	**200**
Laser/cathode				
Shape	flat-top	Gaussian	Gaussian	Gaussian
Length (ps)	8 (fwhm)	3 (rms)	3 (rms)	3 (rms)
Rise/fall time (ps)	0.8	-	-	-
Rms beam size (mm)	0.12	0.12	0.13	0.14
Thermal emittance (mm mrad)	0.108	0.108	0.117	0.126
Gun				
Peak field at cathode (MV/m)	120	120	110	100
Beam launch phase from 0-crosing	47°	47°	46°	44°
Max field of the main solenoid (T)	0.383	0.384	0.356	0.328
Accelerating section				
Entrance of 1st section from cathode (m)	1.9	1.9	1.75	1.6
Gradient of 1st section (MV/m)	14	14	14	14
Gradient of 2nd section (MV/m)	19	19	19	19
Gradient of 3rd section (MV/m)	19	19	19	19
Phase of 1st section from on-crest	$-64°$	$-64°$	$-64°$	$-64°$
Phase of 2nd section from on-crest	17°	17°	17°	17°
Phase of 3rd section from on-crest	17°	17°	17°	17°
Max field of the 1st linac solenoid (T)	0.070	0.068	0.066	0.064
Max field of the 2nd linac solenoid (T)	0.11	0.08	0.10	0.11
Electron beam, simulation				
100% rms projected emittance (mm mrad)	0.123	0.239	0.226	0.222
Slice emittance at center (mm mrad)	0.113	0.120	0.128	0.141
Fwhm bunch length (ps)	7.9	8.1	8.1	8.1
Peak current (A)	26.5	26	26	26
Mean E (MeV)	134.7	134.7	134.5	134.4

0.14 mm mrad. The current profile of a bunch at the injector end was almost the same as for the 120 MV or 110 MV/m cases.

When such lower RF fields are applied at the gun, the phase delay of a bunch through the gun increases and the launch phase at the cathode should be shifted to the direction of zero-crossing phase for the optimum beam dynamics condition. In addition, the solenoid fields were optimized for each cases. The simulation parameters are summarized in Table 1.

SUMMARY

We studied various options for injector operation an low emittance photoinjector using different longitudinal drive-laser profiles and RF field strength at the gun. Both laser profiles show similar slice emittance at the central slices of a bunch even though the projected emittance of both cases shows difference. Reasonably good emittance can be achieved using lower RF fields, 110 MV/m or 100 Mv/m, at the cathode.

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