DESIGN OF A LOW EMITTANCE AND HIGH REPETITION RATE S-BAND PHOTOINJECTOR

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Abstract

One of the key components for the success of VUV or X-ray free-electron lasers (FELs) is the injector. Injectors starting with photocathode RF guns provide high brightness beams and therefore they are being adopted as injectors of VUV or X-ray FELs. In this paper we show how to improve the photoinjector performance in terms of emittance and repetition rate by means of injector components optimization. Transverse emittance at an injector is reduced by optimizing the gun design, gun solenoid position, and accelerating section position. The repetition rate of an injector mainly depends on the gun. By adopting the coaxial RF coupler and improving cooling-water channels of the gun, a maximum repetition rate of 1 kHz will be achieved.

INTRODUCTION

Thanks to their ability to generate an electron beam with low transverse emittance and short bunch length, an injector with a normal conducting photocathode RF gun and a normal conducting linac became an widely adopted option for X-ray FEL projects such as LCLS [1], PAL-XFEL [2], and SwissFEL [3]. The beam quality requirements at the injectors are increasing as more advanced FEL performances are demanded. Any reduction of transverse emittance will help to reduce the FEL gain length and to enhance the FEL brightness. With a given maximum beam energy, a shorter FEL wavelength can be achieved with a smaller transverse emittance.

An RF photoinjector typically consists of a drive-laser, an RF gun with a photocathode, focusing solenoids, and accelerating sections (see Fig. 1). A drive-laser allows an optimal initial shape of an electron beam at the cathode. A strong RF field accelerates immediately the beam emitted at the cathode from zero to a relativistic velocity. The gun solenoid focuses the beam transversely and aligns the beam distribution in transverse phase space so that the projected emittance growth is minimized [4]. With help of the accelerating sections, the beam becomes fully relativistic at the end of the injector and the space charge effect does not increase the beam transverse emittance. In this paper, we discuss how to design and place the accelerator components, such as RF gun, solenoid, and accelerating sections, for best beam quality.

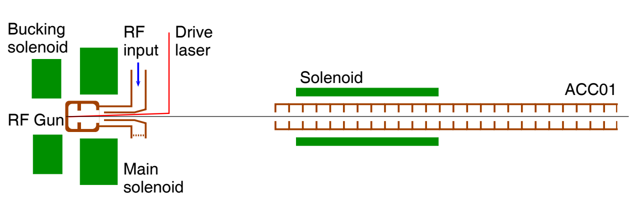

Figure 1: Layout of the first part of the photoinjector. Three more accelerating sections (not shown) follow ACC01 for accelerating a beam to a space charge free regime.

RF GUN

The RF gun, where an electron beam is generated, is the most crucial component in a photoinjector. An electron beam is emitted from the cathode by a drive-laser pulse. The cathode is located at the center of the rear wall of the gun first cell. The emitted electron bunch is accelerated from rest at the cathode to a relativistic velocity at the gun exit by the strong RF accelerating field. During the beam acceleration through the gun, space charge and RF chromatic effects may increase the transverse emittance. Such effects can be minimized by a careful design of the gun as will be shown in this and the next sections.

The beam transverse emittance may be minimum at a combination of first and second cell lengths. Optimization was carried out by repeating particle tracking simulations with ASTRA [5] for various sets of first and second cell lengths. A set of field profiles for various cell lengths were produced by using SUPERFISH code [6]. Since the second cell length was found to be less dominant and the optimum length is close to $\lambda/2$, we fixed the length to $\lambda/2$ (50 mm). Figure 2 shows the transverse emittance at the exit of the gun for the various first cell lengths. For the comparison with the LCLS and DESY guns, the dimensions of both guns were scaled to 2.998 GHz and beam simulations were carried out (see Fig. 2).

For the 28 and 33 mm first cell length cases, the emittances were simulated for various laser beam sizes (Fig. 3). The same laser temporal profile, flat-top with 8 ps fwhm and 1 ps rise/fall time, was used. Compared to the 28 mm case, a larger laser beam is needed for the 33 mm case. For the longer first cell, the beam launch phase for maximum beam energy at the gun exit is shifted toward the zero-crossing phase [7]. Therefore, the RF accelerating field during the beam emission becomes lower and the space charge effect should be reduced by increasing the initial beam size. The intrinsic (thermal) emittance increases linearly with the beam size and the final emittance tends to increase as well. As shown in Fig. 3, the emittance for the 33 mm case and a 0.13 mm rms laser beam size is relatively large because the beam expands fast near the cathode. The emittance values for the 33 mm length becomes close to the cases of the 28 mm length as the laser beam size becomes larger. The calculated emittance values are compared with the thermal emittance. For the thermal emittance calculation 0.6 eV kinetic energy of photoemitted electrons, which produces 0.89 mm mrad per 1 mm rms laser beam size, was used. In this gun design, the first cell length was chosen to

ISBN 978-3-95450-117-5

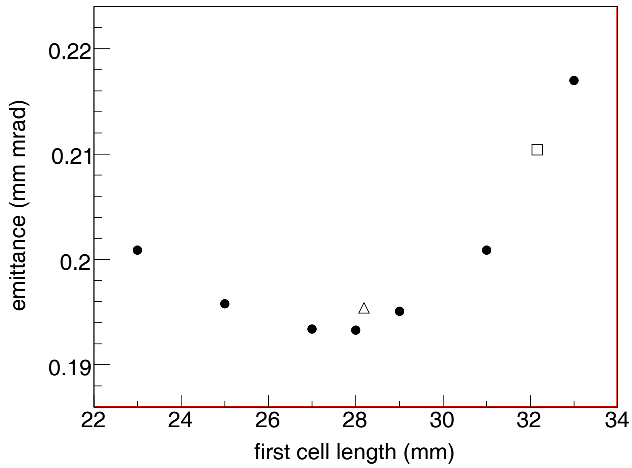

Figure 2: Normalized transverse emittance of 200 pC bunch at the gun exit for various first cell lengths and a $\lambda/2$ second cell length, (•). For comparison, the cases of the DESY (△) and LCLS (□) guns scaled to 2.998 GHz are shown. The gun solenoid was 0.1 m from the cathode. The peak RF field at the cathode was 120 MV/m and the beam launch phase was chosen for the maximum beam energy at the gun exit. A flat-top laser temporal profile with 8 ps length and 1 ps rise/fall time was used. The gun solenoid field and laser beam size were optimized for best emittance condition at each simulation point.

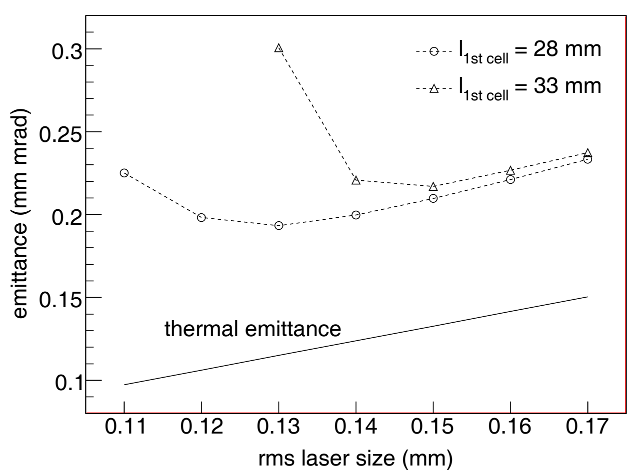

Figure 3: Normalized transverse emittance at the gun exit for various laser sizes. The two first cell lengths ($l_{\mathrm{1st\,cell}}$), 28 and 33 mm, were studied. The thermal emittance is shown for comparison. The same simulation conditions were used as in Fig. 2 unless otherwise mentioned.

be 28 mm.

The second issue of the gun design is the axial symmetry. The broken symmetry with a side coupler may increase significantly the RF emittance and also affect the space charge emittance [8]. A perfect axial symmetry can be achieved by using a coaxial RF coupler connected to the front opening of the gun [9].

The technical design of the gun was discussed in Ref. [10]. Thanks to the coaxial coupler and water-cooling, this gun should be capable of operating with 1 kHz repetition rate at 100 MV/m and or 700 Hz at 120 MV/m.

GUN SOLENOID

The main solenoid focuses a beam and aligns the beam slices to minimize the transverse emittance. The bucking solenoid sitting behind the gun compensates the residual magnetic field at the cathode, which is generated by the main solenoid. If the magnetic field at the cathode is not zero, the residual angular momentum at the end of the main solenoid field increases the beam transverse emittance.

The gun solenoids were designed using the POISSON code [6]. The thickness of the main solenoid is 135 mm. The main solenoid can provide a maximum field of 0.42 T at the beam axis without saturation at the iron yoke.

To find the optimum location of the main solenoid, beam tracking simulations were carried out using the ASTRA code (Fig. 4). The location of the main solenoid center was varied from 0.07 to 0.24 m from the cathode. Two RF peak fields of 100 MV/m and 120 MV/m at the cathode were used. A 200 pC bunch was generated at the cathode with a 8 ps long flat-top laser pulse with 1 ps rise/fall time. The laser pulse size and the beam launch phase at the cathode were optimized at each solenoid position in order to obtain a lowest transverse emittance at the exit of the gun.

As shown in Fig. 4, transverse emittance is smaller when the solenoid position is close to the cathode for both cases of gun fields. For the 120 MV/m field and the 0.09 and 0.10 m solenoid position cases, the emittance was minimum when the launch phase was the same as for the maximum beam energy, 46°, at the exit of the gun. When the solenoid position became closer to the cathode, the launch phase was shifted toward 90°. When the solenoid moved

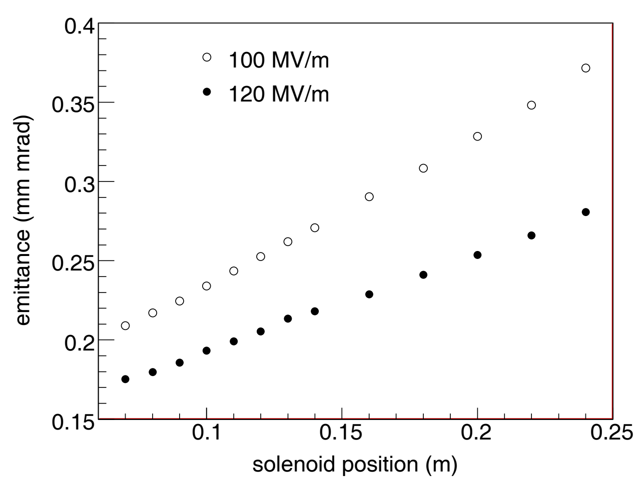

Figure 4: Normalized transverse emittance as a function of the distance between the solenoid center and the cathode at 100 and 120 MV/m peak RF field at the cathode. The simulations were carried out at 200 pC bunch charge.

ISBN 978-3-95450-117-5

downstream, the launch phase was shifted toward the zero-crossing phase. The optimal laser beam size became larger when the solenoid was moved far from the cathode.

INJECTOR PERFORMANCE

After a beam is generated at the gun, the beam is further accelerated to be fully relativistic. Four 3.1 m long, constant gradient traveling-wave structures are used. To allow a 700 Hz repetition rate operation, the maximum gradient of the cavities was set to 15 MV/m, which was scaled down from a 20 MV/m gradient for 400 Hz as discussed in Ref. [11]. For a 1 kHz operation, the maximum cavity gradient was set to 12.5 MV/m.

Low Emittance Injector

For this low emittance injector design, we use 120 MV/m peak gun RF field, 28 mm gun half cell length, 0.1 m gun main solenoid position, and 1.8 m first accelerating section position. A 200 pC beam is generated at the cathode assuming a drive laser pulse with 8 ps fwhm length and 0.12 mm rms size. The laser profile is temporally flat-top with 1 ps rise/fall time and transversely uniform with sharp edge. Electrons photoemitted from the cathode have a 0.6 eV kinetic energy and therefore the intrinsic (thermal) emittance is 0.89 mm mrad per 1 mm rms beam size. 100k macro-particles were generated and tracked using ASTRA.

The radial beam size at the gun section is controlled by the focusing field of the gun main solenoid (Fig. 5). At each of the four accelerating sections, 1.7 m long solenoids are placed. The defocussing force of the traveling-wave accelerating section is compensated by the solenoids around the accelerating tubes. Mild velocity bunching is applied with the first accelerating section, where the RF phase is -60° off the on-crest phase (Fig. 6).

At the end of the injector (20 m from the cathode), a 200 pC bunch has a peak current of 27 A and a slice emittance below 0.13 mm mrad at the central slices (Fig. 7). Other operating conditions were studied with 20 and 50 pC bunches. In these cases the positions of all of the hardware were fixed as for the 200 pC bunch case. The simulation input parameters and results for the three bunch charge cases are summarized in Table 1.

When the gun operates at a peak field of 120 MV/m and the accelerating sections operate at a maximum gradient of 15.2 MV/m, this injector should be capable of operating at 700 Hz repetition rate.

If the kinetic energy of photo-emitted electrons is reduced to 0.15 eV (i.e., a 0.44 mm mrad intrinsic emittance per 1 mm rms initial beam size) as demonstrated in Ref. [12], the emittance can be further reduced. For example, a projected emittance of 0.09 mm mrad and a slice emittance of 0.07 mm mrad are expected for a 200 pC bunch.

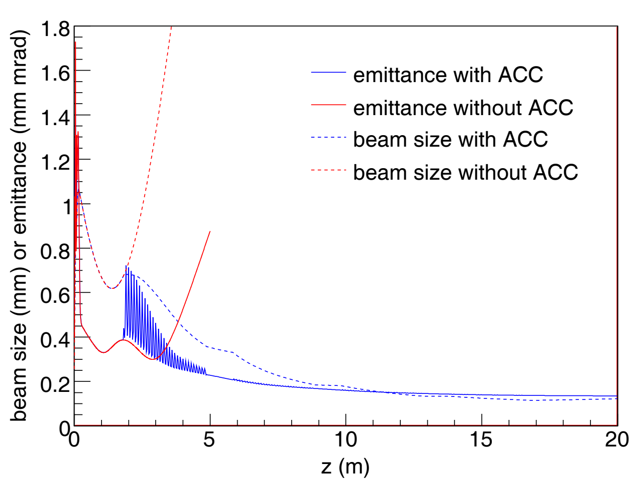

Figure 5: Beam size and emittance evolution from the cathode to the injector end, with and without accelerating sections. 200 pC bunch charge and 120 MV/m peak gun field were used for ASTRA simulation.

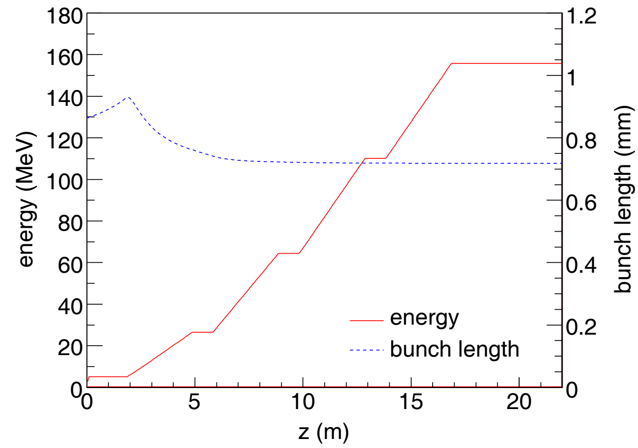

Figure 6: Beam energy and bunch length evolution at 200 pC bunch charge and 120 MV/m gun peak field. The bunch length becomes shorter as the beam propagates through the first accelerating section. The RF phase of the first section was -60° from the on-crest phase.

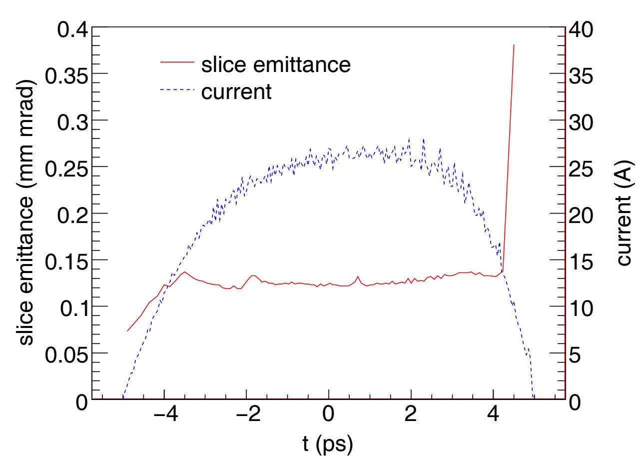

Figure 7: Slice emittance and current profile of a 200 pC beam at the end of the injector.

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Table 1: Parameters of the Injector Simulation for the low Emittance Injector. Beam parameters are shown at the injector end.

Bunch charge (pC)	200	50	20
Laser			
fwhm length (ps)	8	8	4
rise/fall time (ps)	1	1	1
rms radius	0.12	0.06	0.045
thermal ε (mm mrad)	0.106	0.053	0.040
Gun			
peak field (MV/m)	120	120	120
launch phase from 0-crossing	45°	45°	45°
Accelerating modules			
grad of 1st & 2nd (MV/m)	12.5	12.5	12.5
grad of 3rd & 4th (MV/m)	15.2	15.2	15.2
phase of 1st (from on-crest)	−60°	−60°	−60°
Beam at 20 m			
100% rms proj ε (mm mrad)	0.135	0.066	0.049
ε of central slices (mm mrad)	0.127	0.056	0.046
fwhm bunch length (ps)	8.1	4.5	3.8
peak current (A)	27	8.2	5.4
rms slice $\Delta E/E$ ($\times 10^{-5}$)	0.9	0.9	0.5
mean E (MeV)	155.4	155.4	155.4

High Repetition Rate Injector

The possibility of operating this gun at 100 MV/m peak field and 1 kHz repetition rate has been studied numerically in Ref. [10] and the result showed this gun would be thermally stable at that condition. Relatively low gun peak field will also relax the dark current, which may be a potential problem at such a high repetition rate. Due to the reduced gun peak field, the main solenoid position was shifted from 0.10 m to 0.09 m. The first accelerating section position was moved to 1.4 m from the cathode. As the gun peak field is reduced, the beam transverse emittance increases but that is still at a low level (see Table 2). This high repetition rate injector is applicable not only as a baseline injector (1 kHz repetition rate) for the superconducting linac based NLS project [13] but also as an injector for an X-band (or S-band) alternative which is discussed in Ref. [14].

DISCUSSION

We designed a low emittance and high repetition rate injector by numerically optimizing the gun design, the solenoid position, and other machine parameters. A minor improvement of the beam parameter could be achieved by gun cell length optimization. The position of the gun main solenoid was found to be a sensitive contribution to the beam parameter.

By using a coaxial RF power coupler at the gun and applying water-cooling channels around the gun body and at the rear wall and irises, the repetition rate of the gun could increase up to 1 kHz. The maximum gradient of the accelerating sections was reduced for the repetition rate.

Table 2: Parameters of the Injector Simulation for 1 kHz Operation

Bunch charge (pC)	200	50	20
Laser			
fwhm length (ps)	8	8	4
rise/fall time (ps)	1	1	1
rms radius	0.15	0.07	0.05
thermal ε (mm mrad)	0.132	0.62	0.044
Gun			
peak field (MV/m)	100	100	100
launch phase from 0-crossing	41°	41°	41°
Accelerating modules			
grad of 1st & 2nd (MV/m)	10.5	10.5	10.5
grad of 3rd & 4th (MV/m)	12.5	12.5	12.5
phase of 1st (from on-crest)	−20°	−20°	−20°
Beam at 20 m			
100% rms proj ε (mm mrad)	0.175	0.076	0.059
ε of central slices (mm mrad)	0.156	0.067	0.046
fwhm bunch length (ps)	10	8.2	3.8
peak current (A)	21	6.2	5.4
rms slice $\Delta E/E$ ($\times 10^{-5}$)	0.9	0.5	0.5
mean E (MeV)	147.3	147.3	147.3

The low emittance injector design is applicable for normal-conducting linac based X-ray FEL projects such as LCLS, PAL-XFEL, and SwissFEL, which require very high beam quality and relatively low repetition rates. The high repetition rate injector is applicable as a baseline injector for the superconducting linac based NLS project and also as an injector for a normal conducting linac based alternative.

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ISBN 978-3-95450-117-5