SIMULATION ON THE EMITTANCE OF THE RF GUN INCLUDING THE SCHOTTKY EFFECT

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Abstract

The applied electric field strength can affect the electron emission because of the Schottky effect. In the case of rf gun, this effect will cause the electron current varing with the phase of the rf electric field. Especially for the photo-cathode rf gun, the variation is so significant because of the strong rf field, that it cannot be neglected though the electron bunch is only a few pico-seconds long. The charge distribution within the bunch therefore becomes tilted. The emittance of this tilted bunch might be larger than that of the square bunch. The result seems to make the argument that further reducing the beam emittance by shaping the drive laser bunch both in radial space and in time structure be more challenging in the technology point of view. In order to produce a square charge distribution, the laser bunch would probably be required to be time-tilted.

Introduction

The so-called self amplified spontaneous emission might produce coherent radiation in the VUV and the soft x-ray regions with peak brilliance several orders higher than the third generation light sources. However, it demands very stringent qualities of electron beam. In order to meet the requirements, the photo-cathode rf gun injector is basically asked to produce the electron bunches with 1nC charge and 1πmm-mrad normalized transverse emittance. With the adoption of the Carlsten's emittance compensation scheme[1], the emittance growth due to the linear components of space charge forces can be recoveried. The final emittance, thus, can reach about 1πmm-mrad which is already shown in current simulation studies at SLAC[2] and DESY[3].

The emittance compensation technique has its roots in removing the linear correlation between the longitudinal and the transverse phase spaces. One can image that the compensation would be completely done if the correlation is completely linear. So that the charge distributions of electron bunches are necessary to be uniform in both longitudinal and transverse dimensions. In other words, any effects which can cause non-uniform charge distributions in both dimensions would increase the final emittance, because the resulted non-linear correlations cannot be removed by the Carlsten's technique.

At the emittance level of 1πmm-mrad, any small effects which would affect the charge distributions in the processes of emission and acceleration would make contributions to the emittance value. Among them, the drive laser bunch holds the most significant influence since it directly determines the charge distributions of emitted electrons. This effect has been studied in detail in the LCLS collaberation and a technical way has been pointed out. This way is tring to shape the drive laser bunch both transversely and longitudinally into a square bunch[4]. An emittance of less than 1πmm-mradis foreseen through this way. The other effects, such as the space charge force and the rf electro-magnetic force, are taken into account naturally in simulations.

Another effect caused by the Schottky effect, however, is lack of investigation in simulation as far as we know. The Schottky effect means that the accelerating field can increase the current emission because the field reduces the level of the cathode barrier. As the result of the time variety of the rf field, the emission current varies with the rf phase. Because of the strong rf electric field, this variation is so significant that it cannot be ignored though the electron bunch length is only a few pico-seconds. The charge distribution becomes tilted within the bunch . The emittance of this tilted bunch might be larger than that of the square bunch.

This paper will present our simulation results on the effect. The numerical model is simply described in Section 2. Section 3 is the main body of this paper and gives all simulation results. Finally, a summary is given in Section 4.

Numericalmodle

The beam dynamics is calculated using a pc–version of PARMELA[5]. The gun cavity is the LCLS type, 1.6 cell π-mode s-band cavity. In simulations, the Carlsten's emittance compensation is adopted by using a solenoidal magnet. Its position and strength are optimized to obtain the minimum transverse emittance in down stream beam line. Figure 1 shows the schematic layout of the rf gun injector used in our simulations. In Section 3.1 and Section 3.2, the simulations include no accelerating structure. By comparison, the accelerating structure is added in simulations of Section 3.3. The maximum field strength of 140MV/m at cathode is assumed.

The emitted electron bunch is treated as a composition of a series of short gaussian pulses with identical standard deviation σ and different central positions. The rise and

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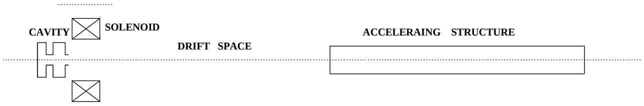

Figure 1: Schematic layout of the rf gun injector used in simulation.

falling time is simply taken as 2σ, the main part of the bunch length is the time difference between the first and the last short gaussian pulses. By varing the height of each seperated gaussain pulses, one can obtain an arbitrary shape of emitted electron bunch. The bunch contains 10,000 big particles in our simulations.

A small code based on above consideration is programmed to produce the bunch shape. Thus, the Schottky effect can be included in simulations. The photoelectron current can be described by,

$$J = aI\left(h\nu - \phi + b\sqrt{\beta E}\right)^2 .$$

Here, J is the total electron current density, I is the laser intensity, $h\nu$ is the photon energy, ϕ is the work function, E is the electric field strength, β is the field enhancement factor, and $b = \sqrt{(e/4\pi\epsilon_0)}$, a is a constant related to the material properties and surface conditions. Notice that this formula implies a linear growth in the photo emission due to the electric field term. However, the reality seems more complicate than the formula. A measurement[6] done at the BNL accelerator test facility showed a higher growth than the linear growth. So that we decided that the Schottky effect would be represented by scaling the BNL's experimental datas into our simulations.

Simulations

Square drive laser bunch

To purify the problem considered, we assume that the drive laser bunch is a nearly square bunch in both transverse and longitudinal dimensions. The bunch radius is 1mm and the bunch length is 10 pico-seconds. Figure 2 shows the PARMELA output of the longitudinal bunch distributions at different positions: the cathode, the end of the first cell, the end of the second cell, and the position with the minimum emittance. The available minimum transverse emittance is 0.94πmm-mrad before the accelerating structure.

Comparing Figure 2a and Figure 2b, a bunching effect is found during the early acceleration stage. This bunching takes place through the normal mechanism of rf acceleration, so that it is strongly relative to the rf phase when the drive laser is triggered. At the phase operating for small emittance, the overall bunching amount is not large. It still can be seen, however, that the electrons are compressed a little more at tail part than at head part. This difference will in principle cause the non-linear space charge force induced emittance growth during behind path. However, the growth is rather smaller than that the other effects caused.

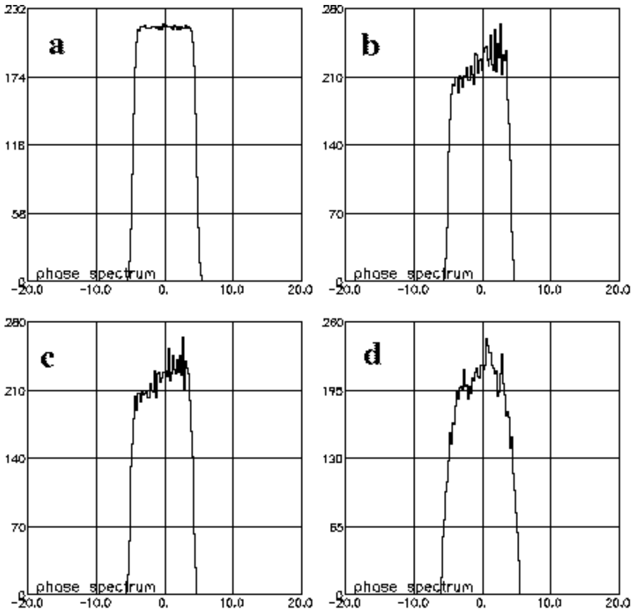

Figure 2: Phase spectrum of the electron bunch at different positions while the Schottky effect is not included. **a**:cathode; **b**:exit of the first cell; **c**:exit of the second cell; **d**:minimum emittance position. The horizontal unit is in pico-second. The vertical unit can be think of the relative intensity. Note, that the head of the bunch is on the left side.

Schottky effect

The schottky effect is introduced into simulations while the drive laser is kept being square. Most other parameters in simulations are kept unchanged also. And those unchanged parameters are found very close to their optimized values for obtaining the minimum emittance. In order to see the minimum emittance value, it is necessary to vary the solenoidal field strength within a certain range. Figure 3 shows the PARMELA output of the longitudinal bunch distributions at the same positions as in Figure 2. It may be surprise to see how large is the current increase caused by the Schottky effect. The current distribution is finally alike a gaussian. The available minimum emittance of this tilted bunch is 1.00πmm-mrad which is by about 0.06πmm-mrad (or about 6%) larger than that of the square bunch case.

Withdown-stream acceleration

Since there is no further acceleration behind the gun cavity in the above calculations, the beam energy is not high enough to suppress the space charge forces. The emittance compensation has to be done rather rudely in order to overcome the counteraction of space charge forces. As a result, the available minimum emittance is larger than that would be reached. Actually, the further acceleration can reduce the space charge forces. Therefore, it will help the emittance compensation taking its effect smoothly and achiev-

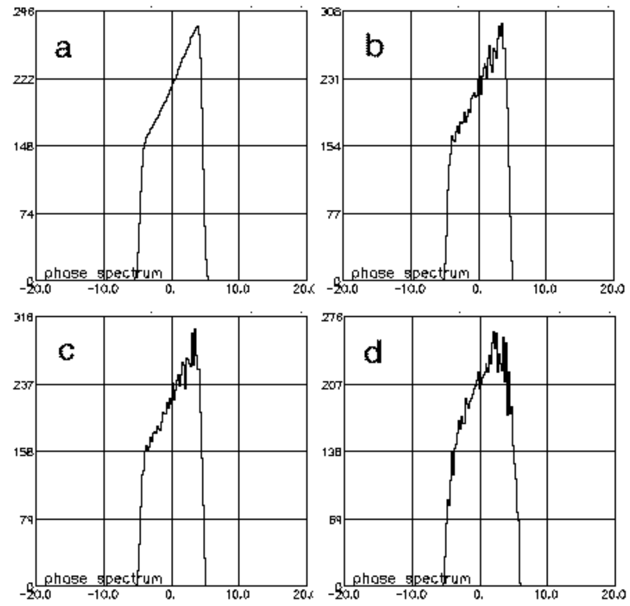

Figure 3: Phase spectrum of the electron bunch at different positions while the Schottky effect is included. **a**:cathode; **b**:exit of the first cell; **c**:exit of the second cell; **d**:minimum emittance position. The horizontal unit is in pico-second. The vertical unit can be think of the relative intensity. Note, that the head of the bunch is on the left side.

ing smaller emittance value. That is proved by simulation and the results are listed in the following table. A 3-meter long SLAC type constant gradient accelerating structure is adopted in our simulations. The accelerating gradient is assumed to be 14MV/m. One can learn that the Schottky effect causes an emittance growth of 0.05πmm-mrad, or a growth about 6%.

	Minimum emittance
No Schottky effect	0.88πmm-mrad
Schottky effect	0.93πmm-mrad

Summary

The influence of the Schottky effect on the beam emittance has been studied in this paper. Comparing with the influences of drive laser bunch shape, for example, the rise and falling time, it is a small effect. This is understandable since the schottky effect changes only the top part of the bunch charge distribution. The effect can be neglected in most cases, even the case in Figure 3 where a large field enhancement is taken account. However, it may worth keeping in mind when tring to achieve very small emittance values. As we already know that square drive laser bunch cannot produce square electron bunch since the Schottky effect, it may be necessary calling for a time-tilted laser bunch. Both the tilted laser and the schottky effect work together, a square electron beam can be produced.

References

[1] B.E. Carlsten,"New photoelectric injector design for the Los Alamos National Laboratory XUV fel accelerator", Nucl. Instr. and Meth. A285 (1985)313.

[2] D. Palmer, "Microwave measurements and beam dynamics simulation of the BNL/SLAC/UCLA emittance compensated 1.6cell photocathode rf gun." presentd at DESY, August 1995.

[3] Yongzhang Huang and Klaus Flöttmann, "Simulation study of the rf gun for the TTF free electron laser." DESY Print, TESLA-FEL 96-01.

[4] R. Tatchyn, et al., "Research and development toward a 4.5–1.5Å linac coherent light source (LCLS) at SLAC". Proc. of FEL'95, Nucl. Instru. & Meth. A375(1996)274.

[5] K. R. Crandall and L. Young, "PARMELA", in the Compendium of Computer Codes for Particle Accelerator Design and Analysis, H. Deaven and K. C. Chan, Eds. Los Alamos Natl. Lab Report LA-UR-90-1766, May(1990)137.

[6] X. J. Wang, X. Qiu and I. Ben-Zvi, "Experimental observation of Micro-bunching in a photocathode rf gun injector". Presented in the mini-workshop of TESLA test facility at DESY, March, 1996.