Title
Note on RF Photo-Cathode Gun

Author
Kim, K.-J.

Publication Date
1990-08-01

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

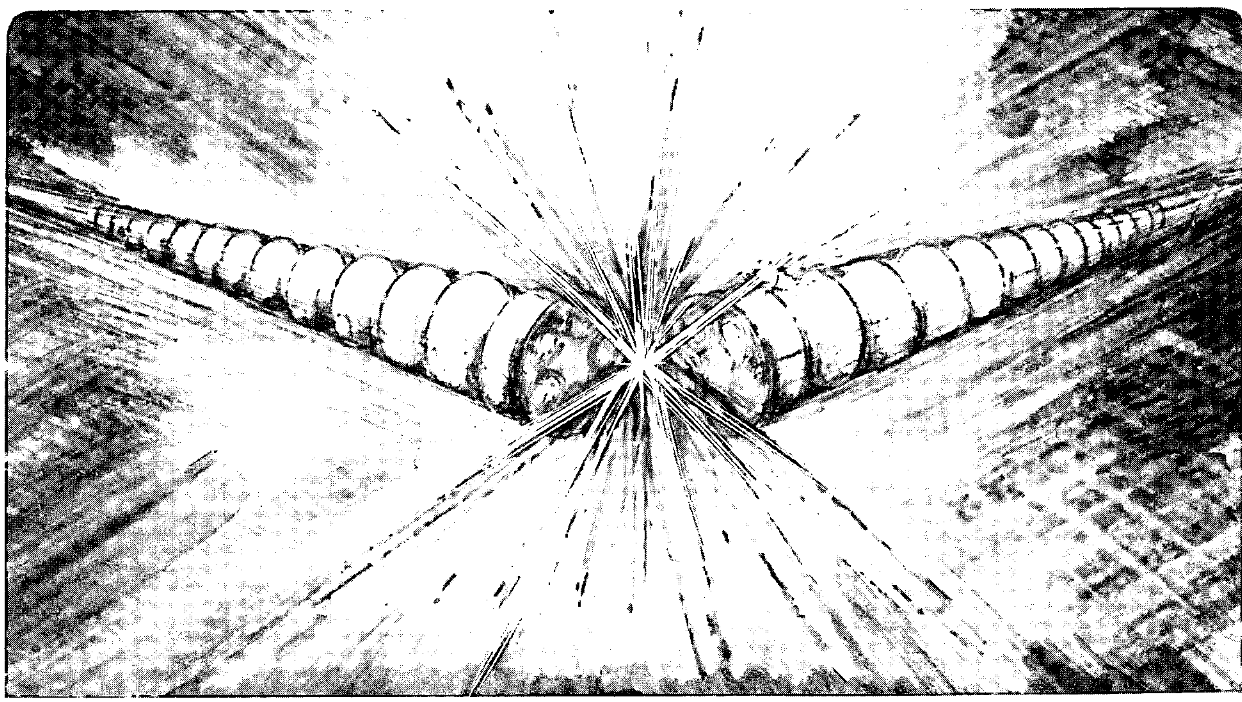
Accelerator & Fusion Research Division

Invited paper presented at the Workshop on
"Prospect for a 1 Å Free-Electron Laser",
Sag Harbor, NY, April 22–27, 1990,
and to be published in the Proceedings

Note on RF Photo-Cathode Gun

K.-J. Kim

August 1990



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

DISCLAIMER

ESG Note-106
LBL-29538

Note on RF Photo-Cathode Gun

Kwang-Je Kim
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

Invited paper presented at the Workshop on "Prospect for a 1 Å Free-Electron Laser,"
Sag Harbor, New York, April 22-27, 1990

To be published in Proceedings of the 1 Å Free-Electron Laser Workshop

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Note on RF Photo-Cathode Gun

Kwang-Je Kim
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

Abstract

The emittance and current density achievable in RF photo-cathode guns are reviewed.

1. Introduction

In this note we review the capabilities of the RF photocathode gun[1]. The subject is important because of potential application in free electron lasers (FELs) and linear colliders.

In Section 2, we discuss the emittance requirement for FEL application. In Section 3, we summarize the intrinsic emittance and current density both for the thermionic gun and the photo-cathode gun. Section 4, we discuss the emittance growth in the RF cavities, due to the time-dependent RF field and due to the space charge effect. A simple model was used to obtain approximate analytical formula for the emittance growth. In Section 5, we discuss two emittance correction methods to remove the emittance growth. The first method uses RF lenses to introduce time-dependent focusing. The second method is to introduce a focusing lens in the non-relativistic region. Two criteria for the second method to work are discussed. Appendix A contains the derivation of these conditions.

2. Emittance Requirements

One of the beam qualities demanded often for advanced accelerators is the so-called brightness. The brightness is defined as current divided by emittance. Here, the emittance is the area in position-angle phase space.

For free-electron laser (FEL) application, the electron beam emittance should be about λ, the wavelength of the radiation. Thus the emittance needs to be small for FEL operation at small wavelength. The current must also be high to ensure enough gain. Thus, electron beams for FEL need to be of high brightness.

For application in high energy physics, the high brightness is required to achieve high luminosity. Also, beam transport through high frequency, high gradient structure requires high brightness beam.

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

For a more precise definition of the emittance, we consider the transverse coordinate x and the dimensionless momentum p_x, where

$$p_x = \beta\gamma x' . \tag{1}$$

Here, x' is the angle, β is the electron speed divided by the light speed, and $\gamma = 1/\sqrt{1-\beta^2}$. The rms emittance is defined to be

$$\varepsilon_x = \sqrt{\langle x^2\rangle\langle p_x{}^2\rangle - \langle x \cdot p_x\rangle^2} . \tag{2}$$

Here, the angular brackets imply taking the average value. The quantity defined by Eq.(2) is known as the normalized rms emittance. It is invariant under adiabatic acceleration, and under linear optical transformation such as free-space propagation and focussing through quadrupoles.

The unnormalized emittance is

$$\varepsilon_x{}^0 = \varepsilon_x / \beta\gamma = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle x \cdot x'\rangle^2} . \tag{3}$$

We can also associate phase space area associated with the radiation field[2]. For TEM_{00} Mode of optical resonator, the rms unnormalized emittance turns out to be

$$\varepsilon_r = \lambda/4\pi . \tag{4}$$

For FEL to work, one must clearly require

$$\varepsilon_x{}^0 \leq \lambda/4\pi . \tag{5}$$

In the literature, one sometimes finds Eq. (5) replaced by $\lambda/2\pi$ based upon qualitative arguments.

As an example, consider an FEL at "water window", λ = 30 Å. With a 1 GeV electron beam, the required normalized emittance will be

$$\varepsilon_x = 5 \times 10^{-7} \text{ m-rad} = 0.5 \text{ mm-mr} . \tag{6}$$

3.2 Photo-cathode Gun

Photo-cathode guns utilize the photo-emission process; a photo-emisssive surface is illuminated by intense laser beams to knock the electrons from the surface. The basic advantage compared to the thermionic gun is that the current density is very high so that bunching is not necessary. Furthermore, the time structure can be controlled by the laser beam, so that the beam time structure can be tailored to match into the RF accelerators without degrading the emittance.

To minimize the emittance blow-up due to the space charge force, the electrons produced at the photo-cathode surface should be quickly accelerated with a high electric field. Since the gradient of a DC field is limited, the photo-cathode surface can be placed in an RF cavity at a position of maximum longitudinal field. The arrangement, shown schematically in Fig. 1, is referred to as the RF photo-cathode gun[1].

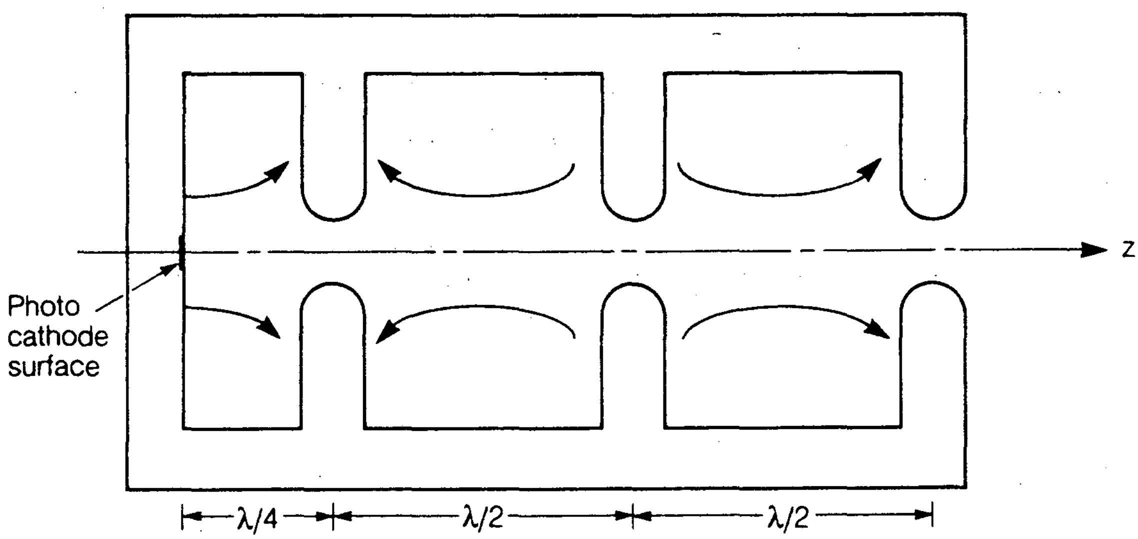


FIGURE 1
Schematics of the rf laser gun.

The intrinsic emittance of the photo-cathode gun is given by an expression similar to Eq. (7):

The required current is typically several hundred Amperes.

In the following, when we say emittance, it will always mean the normalized emittance.

3. Intrinsic Emittance and Current Density

The ultimate performance of a gun is determined by the intrinsic emittance and the current density associated with the emission process from the cathode. We review these values for various cathodes in this section[3].

3.1 Thermionic Gun

Thermionic gun is based on emission from a heated surface. The emittance due to thermal distribution of the electrons is

$$\varepsilon_x = \frac{1}{2} r_c \sqrt{kT/mc^2} \quad . \tag{7}$$

where r_c is the radius of the emitting area, k is the Boltzman Constant, T is the cathode temperature, m is the electron mass , and c is the light speed. Typically, T= 1200° K. For $r_c = 0.6$ cm (corresponding to an emitting area of 1 cm^2), the normalized emittance becomes 1 mm-mrad. This is a very low value.

On the other hand, the current density of a typical thermionic gun is rather modest:

$$J < 10 \text{ A/cm}^2. \tag{8}$$

Thus the gun current will be limited to about 10 A for a typical 1 cm^2 surface area. In order to obtain several hundred Amperes of peak current, it is therefore necessary to pull out a long pulse (several hundred ps) and bunch it to shorter pulse. The bunching process involves non-linearity and mixing of the longitudinal and the transverse phase space, and the emittance is increased significantly. For example, the emittance of the 10 nC pulse for SLC gun[4] after the buncher is 300 mm-mr. Another example is the emittance of the 1 nC, 10 ps pulse for the infrared (IR) FEL design at LBL, which is about 20 mm-mr.

The emittance blow-up can be minimized if the bunching takes place after the beam is accelerated to a sufficiently high energy. However, acceleration of long pulses in RF accelerators requires low frequency and/or harmonic cavity.

$$\varepsilon_x = \frac{1}{2} r_c \sqrt{W/mc^2}; \quad W = h\nu - \phi . \tag{9}$$

Here $h\nu$ is the photon energy and ϕ is the work function. W may be between 0.3 eV and 1 eV. The intrinsic emittance is then

$$\varepsilon_x \approx 3 \times 10^{-4} r_c . \tag{10}$$

This is somewhat larger than the intrinsic emittance for the thermionic gun.

The photo-emissive material can either be semiconductors (CsSb, AsGa, etc.) or metals (Yttrium, etc.). For semiconductor[3],

$$J \approx (100\text{-}500)\ \mathrm{A/cm^2}. \quad \text{(semiconductor)} \tag{11}$$

Thus, current from a 1 cm^2 surface will be several hundred Amperes, enough for short wavelength FEL operation. The intrinsic emittance will be at least about 1.5 mm-mrad. To reduce the emittance further, it is necessary to reduce the surface area with a concomitant decrease in the current.

The semiconductor as photo-cathode has a good quantum efficiency, up to several percent. Potential issue is the lifetime due to poisoning.

For metals, the current density could be much higher[5]:

$$J \approx 10000\ \mathrm{A/cm^2}. \quad \text{(metals)} \tag{12}$$

Thus, it is in principle possible to obtain extremely bright beams using metal surfaces. For example, by using 0.1 cm^2 surface area, a 1000 A beam with emittance 0.15 mm-mrad can be generated.

4. Emittance Growth from RF and Space Charge Effect

The emittance of the RF photo-cathode gun is larger than the intrinsic emittance given by Eq. (9) due to the time variation of the RF field and due to the space charge effect. We summarize the approximate analytical model developed in Ref. (6).

4.1 The Model

In this model, an electron pulse with a given spatial distribution ρ (x, y, Δz) is created at the cathode and is accelerated toward the cavity exit. Here x and y are the transverse coordinates and Δz is the longitudinal coordinate with respect to the bunch center. In order to permit simple calculations, the spatial distribution is assumed to be frozen as the bunch moves in the cavity, i.e., the particles are assumed to move with their relative positions fixed.

The longitudinal electric field (the accelerating field) is assumed to be uniform in the transverse direction, and is given by

$$E_z = E_0 \cos(kz) \sin(\omega t + \phi_0). \tag{13}$$

Here z is the distance from the cathode surface, $\omega = 2\pi f$, f is the RF frequency, and $k = \omega/c$. The transverse components of the electromagnetic field are uniquely determined by Maxwell's equations and are linear in x and y.

4.2 Effect Due to Time Dependent RF

With these assumptions, the net transverse kick to electrons by the RF field occurs only at the cavity exit, with the dimensionless momentum given by

$$p_x = \left(\frac{eE_0}{2mc^2} \sin\left(\phi_f - k\Delta z\right)\right) x \ . \tag{14}$$

Here the exit phase ϕ_f is related to the input phase ϕ_0 by

$$\phi_f = \frac{mc^2 k}{E_0 \sin \phi_0} + \phi_0 \ . \tag{15}$$

Thus, the transverse phase space distribution consists of a collection of lines with different slopes corresponding to different location Δz in the bunch, This is illustrated in Fig. (2). The emittance is a measure of the fan-shaped area in this figure. The area is minimum for

$$\phi_f = 90°. \tag{16}$$

Note that this corresponds to the maximum kick. Thus, there must usually be a strong quadrupoles right next to the cavity exit to focus the beam to a manageable size.

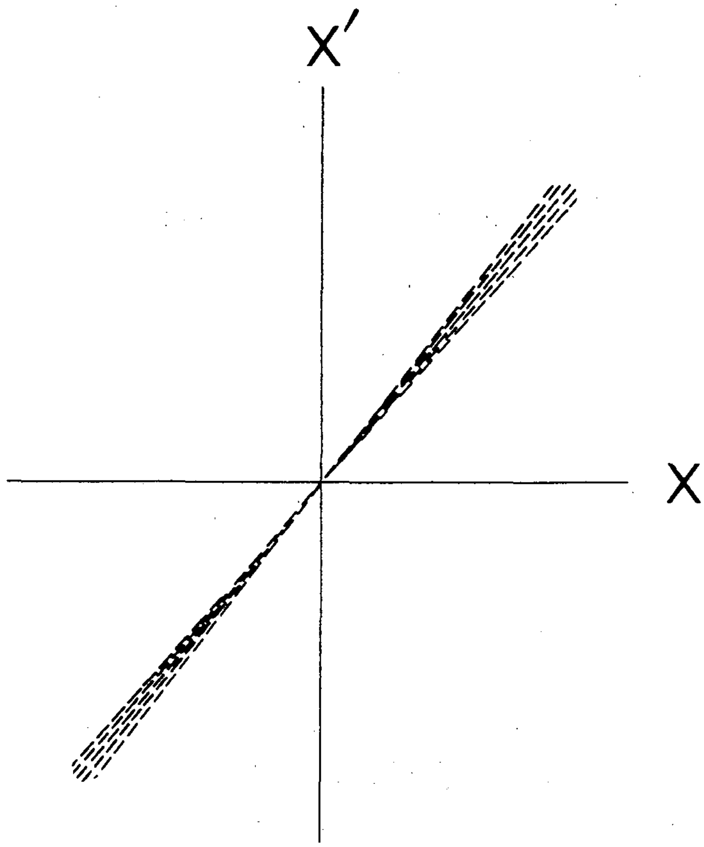


FIGURE 2
Electron distribution in transverse phase space due to time-dependent focusing of the rf field.

Assuming that the electrons' density distribution $\rho(x,y,\Delta z)$ is Gaussian, with the rms transverse and longitudinal sizes given respectively by σ_x and σ_z, the minimum emittance is given by

$$\varepsilon_x^{rf} = \frac{eE_0}{2\sqrt{2}mc^2} k^2 \sigma_x^2 \sigma_z^2 . \tag{17}$$

4.3 Space Charge Effect

The electromagnetic force on an electron due to the rest of the electrons in the bunch, called the space charge force, vanishes as γ^2 as the bunch accelerates to a high energy. It was shown in Ref. (6) that the space charge force can be approximately represented by

$$F_x = mc^2\beta \frac{d}{dz} p_x = \frac{e}{\gamma^2} E_x , \tag{18}$$

where $E = (E_x, E_y, E_z)$ is the electrostatic field due to the charge distribution $\rho(x,y,\Delta z)$. From this and from the relation

$$\frac{d\gamma}{dz} \approx \frac{eE_0}{mc^2} \sin \phi_0 , \tag{19}$$

which follows from Eq. (13) when the electrons are near the cathode surface, we obtain

$$p_x = \frac{1}{E_0 \sin \phi_0} \frac{\pi}{2} E_x . \tag{20}$$

In the above, we assumed that $\gamma = \gamma_f >> 1$ at the exit. The emittance due to the space change effect can now be calculated by inserting Eq. (20) to Eq. (2), the average being calculated with the help of the distribution function $\rho(x,y,\Delta z)$. The result for the Gaussian distribution is approximately given by

$$\varepsilon_x^{sc} = \frac{\pi}{4} \frac{eE_0}{2mc^2} \frac{1}{\sin \phi_0} \frac{I}{I_A} \frac{1}{(3\sigma_x/\sigma_z + 5)} , \tag{21}$$

where I is the peak current and I_A = 17,000A is the Alfven current.

4.4 An Example

Consider the case E_0 = 100 MV/m, the RF frequency $\omega/2\pi$ = 3 GHz, σ_x = 0.6 mm and σ_x = 3.5 mm. This is more or less the parameters for the RF photocathode under construction at BNL.[7] Using Eq. (17) and Eq. (21), we find that

$$\varepsilon_x^{rf} \sim 1 \text{ mm - mrad},$$
$$\varepsilon_x^{sc} \sim 4 \text{ mm - mrad}. \tag{22}$$

These values agree roughly with PARMELA simulation[8]. The transverse emittance for this example is one order of magnitude smaller than that of the state-of-the-art thermionic gun, but still is one order of magnitude larger than that required for an FEL operation at water window, given by Eq. (6)..

5. Emittance Correction Schemes

We have seen in previous section that there is a significant growth in the emittance in the RF cavity to a value much larger than the intrinsic emittance discused in section 3. However, the emittance growth happens more or less in a correlated manner, and can sometimes be corrected. In this section, we discuss the emittance correction schemes to remove the correlated emittance.

5.1 Time-dependent focusing by RF lens

The RF emittance is due to the fact that the phase space slope varies along the length of the bunch. (See Eq. (14) and Fig. 2.) A significant fraction of the phase space blow-up due to space change effect is also similar in nature; the E_x in Eq. (20) varies along the length of the bunch. The emittance blow-up due to such effect can be corrected by introducing a time-dependent lens[9].

$$x' \rightarrow x' + q(t)x \tag{23}$$

where q is a suitable function of time

$$q = a + bt + ct^2. \tag{24}$$

Such a lense can be realized by a properly designed RF cavity. In general, the phase space growth due to RF effect also contains non-linear terms. In that case one attempts to correct it by a non-linear, time-dependent lens:

$$x' \rightarrow x' \rightarrow q_1(t)x + q_3(t)x^3 \tag{25}$$

where q_1 and q_2 are of the form given by Eq. (24). Numerical calculations suggest that the emittance can be reduced by a factor of 3 to 5.

5.2 Focusing in non-relativistic region.

The emittance defined by Eq. (1) is not invariant under linear focusing when non-linear force is present. Thus the possibility exists that, by placing quadrupoles in the region γ~1 where the non-linear space charge force is significant, it may sometimes be possible to reduce the emittance. In fact, within simplified model, it can, under certain conditions, be shown that the contribution to the emittance due to space change effect can be eliminated completely[10]. To see this, we neglect the RF effect and assume that the acceleration is uniform:

$$dz = a d\gamma; \quad a = \frac{mc^2}{e\overline{E}}, \tag{26}$$

where $\overline{E}$ is the average accelerating gradient. Eq. (26) applies near the vicinity of the cathode if we replace $\overline{E} \rightarrow E_0 \sin\phi_0$. Next, we assume that the variation in the transverse coordinate is small, that the particle distribution $\rho(x,y,\Delta z)$ may be regarded frozen for the purpose of calculating the space-charge field. This is a generalization of the model discussed in section 4.1. The equation of motion is given by Eq. (18), where the field E_x is a function of the initial coordinates x_0, y_0, Δz_0, and is independent of z.

Thus, in this model, an electron is emitted from the cathode at (x_0, y_0), parallel to the z-axis ($p_x = 0$, $p_y = 0$) and accelerates toward z>0 under the influence of the space charge force proportional to $E_x(x_0, y_0, \Delta z_0)$. The phase space coordinate after a certain distance from the lens will be of the form

$$\begin{aligned} x &= \alpha x_0 + \beta E_x, \\ p_x &= \gamma x_0 + \delta E_x. \end{aligned} \tag{27}$$

Here, the coefficients α, β, γ, and δ are functions of the focusing strength q. Choosing q such that

$$\alpha\delta - \beta\gamma = 0, \tag{28}$$

the emittance will clearly vanish.

Two conditions must be satisfied for the emittance correction method discussed here to work. First, the lens must be placed at a location where the electrons are still non-relativistic. Second, the variation of the transverse position throughout the entire trajectory must be small so that the model is valid. This latter condition will be violated when the space charge repulsive force is not strong enough; for, in that case, particle trajectory after the focusing lens will at some point cross over the z-axis. In Appendix A we will derive the following explicit forms of these conditions:

$$\ln \gamma_q < 1 , \tag{29}$$

$$\left(\frac{mc^2}{e\bar{E}r}\right)^2 \frac{I}{I_A} \geq 0.5 \ . \tag{30}$$

In the above, γ_q is the electron energy (in unit of mc^2) at the location of the lens, and r is the beam radius.

Equation (30) is not satisfied for the BNL gun discussed in section 4.3. Therefore the emittance correction scheme being discussed here will not work for that case. On the other hand, the inequality is satisfied for the LANL gun for which $\bar{E}$ = 20 MV/m, I = 500A, γ_r = 0.5 cm.

Because of these conditions, especially Eq. (30), the emittance correction method discussed here is not always applicable. Also, the space charge force is always weak at the front and tail ends of the bunch. Therefore, the ends of the bunch have large emittance and need to be removed by a suitable bunch manipulation.

Appendix A

We integrate Eq. (18) by using Eq. (26), and obtain

$$p_x = p_{x1} + \eta(x_0, y_0, \Delta z_0) \int_{\gamma_1}^{\gamma_f} \frac{d\gamma'}{\beta'\gamma'^2} , \tag{A1}$$

where p_1 is the momentum at $\gamma = \gamma_1$, and

$$\eta = \frac{E_x}{\overline{E}} \tag{A2}$$

from Eq. (1),

$$x = x_1 + a\int_{\gamma_1}^{\gamma} \frac{P_x(\gamma')d\gamma'}{\beta'\gamma'} \quad . \tag{A3}$$

To simplify the calculation, we approximate β' in the integrals of (A1) and (A2) by $\beta' \approx 1$. Then

$$p = p_1 + \eta\left(\frac{1}{\gamma_1} - \frac{1}{\gamma}\right),$$

$$x = x_1 + ap_1(\ln\gamma - \ln\gamma_1) + a\eta\left(\frac{\ln\gamma - \ln\gamma_1}{\gamma_1} - \frac{1}{\gamma_1} + \frac{1}{\gamma}\right). \tag{A4}$$

Eq. (A4) gives the transformation of the phase space variable under the space charge force. The transformation under a lens is given by

$$\begin{aligned} x_2 &= x_1, \\ p_2 &= p_1 - qx_1 \end{aligned} \tag{A5}$$

Where (x_1, p_1) and (x_2, p_2) are the phases space variables before and after the quadrupole, respectively.

The transformation under the combined effects of the space charge force and the lens is obtained from Eqs. (A4) and (A5), starting from the initial phase space coordinate $(x_0,0)$ at the cathode surface. The final phase space coordinates are found to be

$$x = x_0[1 - aq(\ln\gamma - \ln\gamma_q)] + a\left[\left(\ln\gamma + \frac{1}{\gamma} - 1\right) - qa\left(\ln\gamma_q + \frac{1}{\gamma_q} - 1\right)(\ln\gamma - \ln\gamma_q)\right]\eta, \tag{A6.a}$$

$$p = -qx_0 + \left[\left(1 + \frac{1}{\gamma}\right) - qa\left(\ln\gamma_q + \frac{1}{\gamma_q} - 1\right)\right]\eta\,. \tag{A6.b}$$

Here γ_q is the value of γ at lens. Note that this equation is indeed in the form of Eq. (27).

The emittance can be calculated from Eq. (A6) and Eq. (2):

$$\varepsilon_x = \sqrt{C(q)}\sqrt{\langle x_0^2\rangle\langle\eta^2\rangle - \langle x_0\eta\rangle^2}\,, \tag{A7}$$

where

$$C(q) = 1 - \frac{1}{\gamma} + aq\left[\frac{1}{\gamma}(\ln\gamma - \ln\gamma_q) + \frac{1}{\gamma} - \frac{1}{\gamma_q}\right]. \tag{A8}$$

The second factor in Eq. (A7) can be interpreted as ε_x^{sc} calculated in Eq. (21). This is because η given by Eq. (A2) is an approximation to the RHS of Eq. (20).

The emittance vanishes for C(q) = 0. It can be shown that this corresponds to Eq. (28). For $\gamma \to \infty$,

$$C(q) = 1 - \frac{aq}{\gamma_q}\,. \tag{A9}$$

Thus the required quadrupole strength for emittance to vanish at $\gamma \to \infty$ is

$$q = \frac{\gamma_q}{a}\,. \tag{A10}$$

Inserting Eq. (A10) into (A6.a)

$$x = (\gamma_q \ln\gamma)\left[-x_0 + (1 - \ln\gamma_q)\eta a\right]; \quad \gamma\to\infty\,. \tag{A11}$$

We now require that x be of the same sign as x_0x_j. Otherwise, the trajectory must have crossed the z-axis at some point and the model breaks down. As the space charge force is repulsive, the function η is of the same sign as that of x_0. Therefore it follows from Eq. (A11) that

$$\ln \gamma_q < 1 \,. \tag{A12}$$

This is Eq. (29), which is the precise version of the statement that the lens must be placed in a sufficiently non-relativistic region.

Having satisfied Eq. (A12), we have to also satisfy the following condition in order that x and x_0 are of the same sign:

$$\eta a > \frac{x_0}{1 - \ln \gamma_q} > x_0 \,. \tag{A13}$$

This inequality will always break down near the front and tail ends of the bunch, as mentioned before. To understand the meaning of the condition (A13) in the middle of the bunch, we evaluate η for a cylindrical bunch of radius r. We find that Eq. (A13) becomes

$$\left(\frac{mc^2}{e\bar{E}r}\right)^2 \frac{I}{I_A} \geq 0.5 \tag{A14}$$

This reproduces Eq. (30).

References

1. J.S. Fraser, R.L. Sheffield, E.R. Gray and P.M. Giles, "Photo-cathodes in Accelerator Applications," Proc. 1987 Particle Accelerator Conf., IEEE Cat. No. 87 CH 2387-9, 1705 (March, 87).

2. K-J. Kim, "Brightness, Coherence and Propagation Characteristics of Synchrotron Radiation", Nucl. Instr. Meth. A246, 71 (1986).

   See also K-J. Kim "Characteristics of Synchrotron Radiation", in AIP Conference Proc. 184, p. 565 (1989).

3. P.E. Oettinger, "A Selection of High-Brightness, Laser-Driven Cathodes for Electron Accelerators and FELs", in Proc. ICFA Workshop on Low Emittance e^--e^+Beams, J.B. Murphy and C. Pellegrini, eds., p. 153, BNL Publication, BNL 52090 (1987).

4. M. B. James, J.E. Clendenin, S.D. Ecklund, R.H. Miller, "Update on the High-Current Injector for the Stanford Linear Collider", IEEE Trans. Nucl. Sciences, Vol. NS-30, 2992 (1983).

5. J. Fischer and T. Srinivasan-Rao, "Short-Pulse High-Current-Density Photoemission in High Electric Field", in Proc. of ECPA Workshop, "New Developments in Particle Accelerator Techniques," S. Turner, ed., p. 506, CERN 87-11 (1987).

6. K-J. Kim, "RF and Space Charge Effects in Laser-Driven RF Electron Guns", Nucl. Instr. Meth., A275, 201 (1989).

7. K. Batchelor, et al, " The Brookhaven Accelerator Test Facility", Proc. 1988 Linear Acc. Conf., CEBAF Report 89-001, 540 (1988).

8. K-J. Kim and Y-J. Chen, "RF and Space Charge Induced Emittances in Laser-Driven RF Guns", Proc. 1988 Linear Acc. Conf., ibid., 322.

9. J.C. Gallardo and R.B. Palmer, "Preliminary Study of Gun Emittance Correction", BNL preprint, BNL-43862 (1990).

10. B. Carlsten, "New Photo-electric Injector Design for the Los Alamos National Laboratory XUV FEL Accelerator," Nucl. Instr. Methods, A285, 313 (1989).

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
INFORMATION RESOURCES DEPARTMENT
1 CYCLOTRON ROAD
BERKELEY, CALIFORNIA 94720