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Second-Order Emittance Compensation in an RF Photoinjector Using RF Radial Focusing

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Abstract

Emittance compensation using the static axial magnetic field from a solenoid surrounding an rf photoinjector has been used to reduce the rms emittance of the electron beam by up to an order of magnitude, for photoinjectors ranging from 433 MHz to 8 GHz. The residual emittance after standard solenoidal compensation depends primarily on how linear the space-charge force is along the electron bunch in terms of an axial Taylor expansion, and is typically a strong function of both solenoid position and focusing strength. In this paper, we investigate the concept of second-order emittance compensation using the combination of a solenoid and radial rf focusing. We numerically demonstrate that (1) lower residual emittances are possible if second-order compensation is introduced by adding radially focusing rf forces in the first photoinjector cavity near the cathode, (2) the residual emittance is less sensitive to solenoid position, (3) the residual emittance is less sensitive to solenoid strength, and (4) the optimal solenoid position is further from the photoinjector cathode, leading to less stringent design requirements, especially at high frequencies.

Emittance compensation [1-6] is a technique used to reduce the rms beam emittance of an electron photoinjector. The basic idea is to use a solenoid magnet to manipulate the beam's transverse phase space distribution in a manner that nonlinear space-charge forces after the solenoid counter the emittance-growth effect of the nonlinear space-charge forces before the solenoid, resulting in a residual emittance much smaller than the peak emittance at the center of the solenoid. Standard treatments [3,5] and experiments [4] assume the beam is quasilaminar, with no appreciable initial beam convergence. A major design issue with the standard compensation technique is to properly place the magnetic center of the solenoid relative to the cathode; for high frequencies, physical design constraints due to the small size of the photoinjector conflict with the optimum placement. Here we demonstrate that by using second-order compensation with rf focusing, both lower emittances and reduced design constraints are possible.

The compression mechanism in a drift can be easily demonstrated [3], where we use the normalized radial force at the edge of the beam, $\hat{\Lambda} = eF_r / m\gamma\beta^2 c^2$, where F_r is the total radial force, m is the electronic mass, γ is the relativistic mass factor, and β is the particle velocity normalized to the speed of light c . Here we extend the analysis of [3] to include the effect of an initial beam convergence, which we will assume we can control by varying the amount of radial rf focusing near the cathode. The analysis will demonstrate that better compensation (lower residual emittances) is possible with the addition of an initial beam convergence (introduced through the effect of the rf focusing). The radial position and divergence of a particle after a drift of length z are given by

$$\frac{r(\rho, \zeta, z)}{\rho} = r_0 + \int_0^z \int_0^{z'} \hat{\Lambda}(\zeta, z'') dz'' dz' + r'_0 z \quad (1)$$

and

$$\frac{r'(\rho, \zeta, z)}{\rho} = \int_0^z \hat{\Lambda}(\zeta, z') dz' + r'_0, \quad (2)$$

where r_0 is the initial beam edge radius, r'_0 is the initial beam edge convergence, ρ is a particle's relative radial position within the bunch ($\rho = 0$ is at the center of the bunch and $\rho = 1$ is at the radial edge of the bunch), and ζ is a particle's relative axial position in the bunch ($\zeta = 0$ defines the axial center and $\zeta = \pm 1$ defines the axial edges of the bunch). Note that we are assuming that the radial forces are radially linear. The normalized radial force $\hat{\Lambda}$ can include both space-charge, magnetic, rf, and other external radial forces. We will also assume that r'_0 vanishes in the absence of radial rf forces. After a drift z_d following a lens with focal length f located at $z = z_l$, the particle positions and divergences are given by

$$\begin{aligned} \frac{r(\rho, \zeta, z_l + z_d)}{\rho} &= r_0 \left(1 - \frac{z_d}{f} \right) + \int_0^{z_l + z_d} \int_0^{z'} \hat{\Lambda}(\zeta, z'') dz'' dz' \\ &\quad - \frac{z_d}{f} \int_0^{z_l} \int_0^{z'} \hat{\Lambda}(\zeta, z'') dz'' dz' + r'_0(z_l + z_d) - \frac{r'_0}{f} z_l z_d \end{aligned} \quad (3)$$

and

$$\frac{r'(\rho, \zeta, z_l + z_d)}{\rho} = \int_0^{z_l + z_d} \hat{\Lambda}(\zeta, z') dz' - \frac{1}{f} \int_0^{z_l} \int_0^{z'} \hat{\Lambda}(\zeta, z'') dz'' dz' - \frac{r_0}{f} + r'_0 - \frac{r'_0}{f} z_l. \quad (4)$$

We expand the radial force about some axial location ζ_0 ,

$$\hat{\Lambda}(\zeta, z) = \hat{\Lambda}(\zeta_0, z) + \chi \hat{\Lambda}'(\zeta_0, z) + \frac{\chi^2}{2} \hat{\Lambda}''(\zeta_0, z) + \dots \quad (5)$$

where we have defined $\chi = \zeta - \zeta_0$ and the derivatives are with respect to ζ . If we keep the first- and second-order expansion terms, the particles' radii and divergences at $z = z_l + z_d$ are given by

$$\frac{r(\rho, \zeta)}{\rho} = \chi \left(a_1 - b_1 \frac{z_d}{f} \right) + \frac{\chi^2}{2} \left(a_2 - b_2 \frac{z_d}{f} \right) + (a_0 + r_0 + r'_0(z_l + z_d)) - (r_0 + b_0 + r'_0 z_l) \frac{z_d}{f} \quad (6)$$

and

$$\frac{r'(\rho, \zeta)}{\rho} = \chi \left(c_1 - b_1 \frac{1}{f} \right) + \frac{\chi^2}{2} \left(c_2 - b_2 \frac{1}{f} \right) + (c_0 + r'_0) - (r_0 + b_0 + r'_0 z_l) \frac{1}{f} \quad , \quad (7)$$

where the coefficients a_i , b_i , and c_i are given by

$$a_i = \int_0^{z_l+z_d} \int_0^{z'} \hat{\Lambda}^{(i)}(\zeta_0, z'') dz'' dz' \quad , \quad (8)$$

$$b_i = \int_0^{z_l+z_d} \int_0^{z'} \hat{\Lambda}^{(i)}(\zeta_0, z'') dz'' dz' \quad , \quad (9)$$

and

$$c_i = \int_0^{z_l+z_d} \hat{\Lambda}^{(i)}(\zeta_0, z') dz' \quad , \quad (10)$$

and the superscript refers to the order of the axial derivative. The normalized force can be redefined to include axial acceleration, if required, without requiring modification of the form of these equations. Emittance compensation is achieved when the ratio of r' to r is independent of ζ (or equivalently χ), or

$$\frac{d}{d\chi}\left(\frac{r'}{r}\right) = \frac{1}{r^2}\left(r\frac{dr'}{d\chi} - r'\frac{dr}{d\chi}\right) = 0 \quad . \quad (11)$$

Inserting Eqns. (6) and (7) into the last parentheses, we find that terms cubic in χ and quadratic in $1/f$ cancel and we end up with this expression for the focal length (exact up to second order in χ):

$$\frac{1}{f} = -\frac{A}{B} \quad , \quad (12)$$

where the numerator A is given by

$$A = \chi[a_2(c_0 + r'_0) - c_2(a_0 + r_0 + r'_0(z_l + z_d))] + \chi^2(c_1a_2 - a_1c_2) + a_1(c_0 + r'_0) - c_1(a_0 + r_0 + r'_0(z_l + z_d)) \quad (13)$$

and the denominator B is given by

$$B = \chi[-b_2z_dc_0 + b_2(a_0 + r_0 + r'_0z_l) + (a_2 - z_dc_2)(b_0 + r_0 + r'_0z_l)] + \chi^2(-b_2z_dc_1 - b_1a_2 + a_1b_2 + b_1c_2) + [-b_1z_dc_0 + b_1(a_0 + r_0 + r'_0z_l) + a_1(b_0 + r_0 + r'_0z_l) - c_1(b_0 + r_0 + r'_0z_l)z_d] \quad . \quad (14)$$

In general, equations (12), (13), and (14) lead to a focal length solution that depends on the axial position χ within the bunch, and, as such, does not lead to emittance compensation. However, there are two important cases in which the focal length is independent of the axial position within the bunch: (1) We assume the second order Taylor expansion terms k_2 are all negligible, compared to the k_1 terms. Then, the coefficients for the linear and quadratic terms of χ vanish for both A and B . Note that the Taylor expansion terms k_1 are of the same sign, and must be nonzero for a physical solution of the focal length (real and positive). Thus, the first-order compensation is not

centered about the middle of the electron bunch, but rather somewhat off to one side or the other (which side depends on what is required to make f positive). This is the only type of approximate compensation possible without rf focusing. (2) At the center of the bunch, the first-order Taylor expansion terms k_1 vanish, leaving in both A and B just the terms linear in χ , which cancels out in the expression for the focal length. The focal length is given by the simpler expression

$$\frac{1}{f} = -\frac{a_2(c_0 + r'_0) - c_2(a_0 + r_0 + r'_0(z_l + z_d))}{-b_2 z_d c_0 + b_2(a_0 + r_0 + r'_0 z_l) + (a_2 - z_d c_2)(b_0 + r_0 + r'_0 z_l)} \quad (15)$$

which is independent of χ and describes a case of second-order emittance compensation. Because this compensation is now valid through the quadratic term of the axial Taylor expansion of the net radial force, this type of compensation leads to a lower residual emittance than that compensating only the linear Taylor expansion term.

In general, this equation is hard to interpret, but we can gain useful insight and qualitative observations if we assume that the normalized radial force $\hat{\Lambda}$ is independent of z . In this case,

$$\begin{aligned} a_i &= \frac{\hat{\Lambda}^{(i)}}{2} (z_l + z_d)^2 \\ b_i &= \frac{\hat{\Lambda}^{(i)}}{2} z_l^2 \\ c_i &= \hat{\Lambda}^{(i)} (z_l + z_d) \end{aligned} \quad (16)$$

and Eqn. (15) for the focal length becomes

$$\frac{1}{f} = \frac{(z_l + z_d) \hat{\Lambda}^{(2)} r_0 + r'_0 (z_l + z_d)^2 \frac{\hat{\Lambda}^{(2)}}{2}}{-z_d^2 r_0 \frac{\hat{\Lambda}^{(2)}}{2} + \hat{\Lambda}^{(2)} r'_0 z_l (z_l^2 - z_d^2 / 2)} \quad (17)$$

Note that even the second-order derivatives of the normalized radial force cancel in this expression. If r'_0 vanishes, this will always lead to an unphysical negative focal length. However, as the magnitudes of r'_0 and z_l increase, a physical, positive solution for the focal length can be found. Thus we predict that for second-order compensation in a photoinjector, we need the combination of rf focusing and the solenoid to be located sufficiently far from the cathode (sufficiently large z_l).

We now present numerical simulations using the particle tracking code PARMELA [7] of the SLAC-BNL-UCLA 1.6-cell, 2.856-GHz photoinjector, with a 1-nC, 10-ps electron bunch. We have included the effect of rf focusing by mixing in various levels of a TM_{011} mode into the first cell, using the field components

$$\begin{aligned} E_z &= AJ_0(k_c r) \sin(\beta_d z) \\ E_r &= -A \frac{f}{f_c} J_1(k_c r) \cos(\beta_d z) \sqrt{1 - (f_c / f)^2} \\ B_\theta &= -A \frac{f}{f_c} J_1(k_c r) \sin(\beta_d z) \end{aligned} \quad (18)$$

where $\beta_d = \pi / 2d$, $f_c = f \sqrt{1 - (\beta_d c / 2\pi f)^2}$, and the cutoff wavenumber is $k_c = 2\pi f_c / c$, and where the axial length of the TM_{011} mode d is an input parameter (typically 5 cm). The radial electric field of this mode is strongest near the surface of the cathode, providing immediate rf focusing and equivalent initial beam convergence. The axial electric field is small compared to the dominant accelerating mode. The following simulations were of the 1.6-cavity photoinjector followed by a long drift. The emittances plotted in Figures 1-3 were the minimum emittances seen anywhere along the drift; in principle that minimum emittance could be the final emittance at high energy, with proper matching of the gradient of the subsequent accelerating sections.

The solid line in Figure 1 shows the dependence on the minimum residual emittance as a function of the normalized magnetic field strength of the compensation solenoid for the case the magnetic center of the solenoid is at 21 cm from the cathode (the solid line is without rf focusing; optimum rf focusing was included in the calculations of the dashed line). Note that the minimum emittance achievable has been decreased by

nearly 40% by the inclusion of rf focusing. In Figure 2 we plot the minimum residual emittance for the case where the solenoid strength was fixed to 0.7, as the rf focusing was changed. Note that the residual emittance is not a strong function of the rf focusing, and is quite low for a wide range of rf focusing. In Figure 3 we plot the minimum achievable residual emittance as a function of the position of the solenoid's magnetic center from the cathode. Note that adding the rf focusing decreases the emittance only when the magnetic center is sufficiently far from the cathode location, and that the residual emittance does not degrade as the magnetic center moves further from the cathode, both in agreement with Eqn. (17).

It is easy to numerically determine that the emittance is reduced by the induced initial beam convergence (as opposed to the time-dependent rf focusing countering the time-dependent nature of the space-charge forces), by verifying that the sinusoidal time function of the added TM_{011} mode is not essential; the same reduction of the residual emittance occurs even if the TM_{011} mode is numerically considered static. Also, the precise form of the mode producing the rf focusing is not critical. Simulations using varied radial force profiles all showed essentially the same amount of reduction in the residual emittance. In practice, rf focusing can be introduced by recessing the cathode slightly [8].

In summary, we have numerically shown that adding rf focusing to introduce an initial convergence of the beam in an rf photoinjector can lead to reduced residual emittances, which are less sensitive to solenoid strength and position. Using a simplified model for the compensation dynamics, we have been able to predict some qualitative features of the second-order compensation, including the requirement for a sufficiently large drift before the magnetic center of the solenoid. The reduced design constraints for the solenoid's axial position may make this approach especially attractive for photoinjectors at high frequency.

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Figure Captions

1. Minimum emittance downstream versus normalized solenoid magnetic field strength without rf focusing (solid line) and with rf focusing (dashed line).
2. Minimum emittance downstream versus normalized rf focusing strength, for the nominal solenoid focusing case.
3. Minimum emittance downstream versus solenoid lens magnetic center (optimizing the rf focusing and the solenoid strength) without rf focusing (solid line) and with rf focusing (dashed line).

Emittance versus Magnetic Field

Emittance versus Amount of RF Focusing

Emittance versus Lens Magnetic Center