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A Two-Frequency RF Photocathode Gun

D.H. Dowell[1], M. Ferrario[2], T. Kimura[3], J. Lewellen[4], C. Limborg[1], P. Raimondi[5], J.F. Schmerge[1], L. Serafini[5], T. Smith[3] and L. Young[6]

[1] SLAC, [2] INFN-Frascati, [3] Stanford University, [4] Argonne National Laboratory, [5] INFN-Milan, [6]Los Alamos National Laboratory

Abstract

In this paper we resurrect an idea originally proposed by Serafini[1] in 1992 for an RF photocathode gun capable of operating simultaneously at the fundamental frequency and a higher frequency harmonic. Driving the gun at two frequencies with the proper field ratio and relative phase produces a beam with essentially no rf emittance and a linear longitudinal phase space distribution. Such a gun allows a completely new range of operating parameters for controlling space charge emittance growth. In addition, the linear longitudinal phase space distribution aids in bunch compression. This paper will compare results of simulations for the two-frequency gun with the standard rf gun, and the unique properties of the two-frequency gun will be discussed.

PACS codes: 29.25.Bx,29.27.Ac,41.60.Cr,41.85.Ar

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1. Introduction

The rf gun transverse emittance is predominately due to space charge forces, rf fields and thermal emittance. Emittance compensation does well to remove the linear space charge contribution, but the gun parameters are still constrained to operate between the space charge and rf limits. This is illustrated in Figure 1, where the uncompensated emittance at the gun exit is plotted in the plane defined by beam size and bunch length. The operating region is shown for the LCLS gun and is typical of most guns. They perform best in the saddle between the space charge and rf dominated regimes. Emittance compensation extends the region into the space charge regime, and does a remarkably good job of recovering the emittance where the correct combination of solenoid, drift and linac gradient and phase, reduce the projected emittance from three microns to one micron after acceleration to high energy. However further improvement requires one to advance from compensating to eliminating the sources of the emittance.

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Stanford Synchrotron Radiation Laboratory, Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

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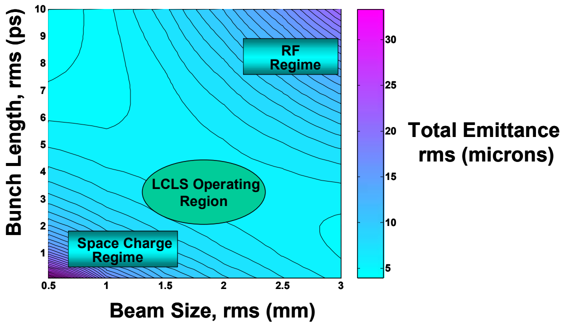

Figure 1. Contour plot of the total emittance at the gun exit in the plane of bunch size and length. The bunch charge is 1 nC. The formulas of Travier [2] were used to compute the rf and space charge effects.

It has been has been shown [1] that the addition of a harmonic to the rf fundamental field would greatly reduce the rf emittance, allowing complete freedom of beam size and length to control the space charge forces. This work showed a harmonic rf field in the same N+1/2 cells as the fundamental will linearize the rf force to 4th order, both transversely and longitudinally. This condition is achieved when the bunch exit phase is $\pi/2$, n=3,7,11… and the n-th harmonic field, E_n, in terms of the fundamental field, E_0, is given by

$$E_n = (-1)^{(n-3)/2} E_0 / n^2$$

This work resurrects these ideas and applies them to the BNL/SLAC/UCLA gun. The space charge and rf dominated regimes are simulated with a new version of Parmela [3] capable of superimposing the rf fields at two frequencies in the same cell. Short bunches are used to explore the space charge dominated regime while long bunches investigate the rf dominated regime. In addition, the two frequency gun is combined with emittance compensation to achieve very low transverse emittance. Comparisons of the transverse and longitudinal emittances and phase space distributions are presented and discussed.

2. Superfish Fields

The standard 1.6 cell BNL/SLAC/UCLA cell shape was modified to have the desired fundamental and 3rd harmonic frequencies while keeping the 1.6 $\lambda/2$ length. The field shapes for the Superfish model are shown in Figure 2. The gun's fundamental mode is unbalanced due to the shape change used to obtain the harmonic. The cathode cell 3rd harmonic is a TM021-like mode and the full cell mode is TM012-like, which shouldn't significantly affect our results since the beam samples only the on-axis fields.

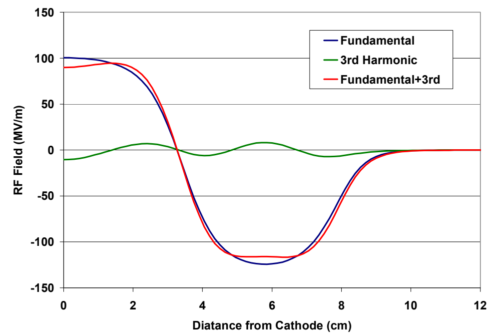

Figure 2. The Superfish fields used in the Parmela simulations. The full cell field is approximately 20% higher than the cathode cell field.

3. The Parmela Simulations

The simulations were designed to explore the two-frequency gun's properties in both the space charge and rf regimes. The study compares emittances for short, space charge-dominated bunches with emittances for long, rf-dominated bunches. The longitudinal electric field is assumed to be the sum of the fundamental and the 3rd harmonic fields given by

$$E_z = E_0 \cos(kz)\sin(\omega t + \phi_0) + E_3 \cos(3kz)\sin(3(\omega t + \phi_3))$$

In each case, the parameters ϕ_0, E_3 and ϕ_3 are varied to obtain the lowest projected emittance.

For both the short and long bunch simulations, the beam size on the cathode is 2 mm radius, flat top distribution and the results are given at the gun exit, with no solenoid field or any emittance compensation The space charge regime (short bunch) uses a 10 ps full width, square bunch shape. The rf regime (long bunch) is studied with a 40 ps long bunch. Simulations are performed with 0 nC and 1 nC to separate the rf and space charge contributions.

For the emittance compensated case the beam radius is 1 mm and the full width bunch length is 30 ps. In all cases, the thermal emittance is zero.

3.1 Longitudinal Phase Space

Figure 3 shows that even for short bunches 3rd harmonic linearization improves the longitudinal phase space. The full width, correlated energy spread is reduced from 100 keV to 40 keV in the presence of space charge.

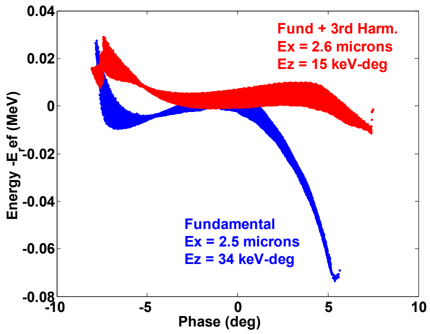

Figure 3. The short bunch longitudinal phase space at 1 nC with and without the 3rd harmonic: E_0=82MV/m, ϕ_0=25 degrees, E_3=-21MV/m, ϕ_3=17 degrees.

The short bunch case for 0 nC, rf only, is shown in Figure 4. The addition of the 3rd harmonic not only makes the distribution more linear, but also flips the sign of the correlation. This is not observed in the analytic theory [1], and is due to the 1.6 cell length of the gun used in these simulations. The original theory is for a 1.5 cell gun. In addition, the figure shows the fundamental phase which produces the lowest transverse emittance is slightly different than that which best linearizes the longitudinal phase space.

The 40 ps long bunch for a 1 nC bunch is shown in Figure 5. With only the fundamental, the bunch has been compressed approximately a factor of two. However, with the 3rd harmonic, the bunch length is unchanged.

3.2 Transverse Emittance

It is expected that the 3rd harmonic should mostly benefit long bunches in the rf dominant regime. In this case, the rf emittance is expected to be small over a wide range of injection phases as given in the original work [1]. Figure 6 shows this is verified by the Parmela simulations, reducing the rf emittance a factor of four or more for injection phases from 25 to 55 degrees. With the addition of space charge, the fundamental + 3rd harmonic emittance is approximately half that of the fundamental only value.

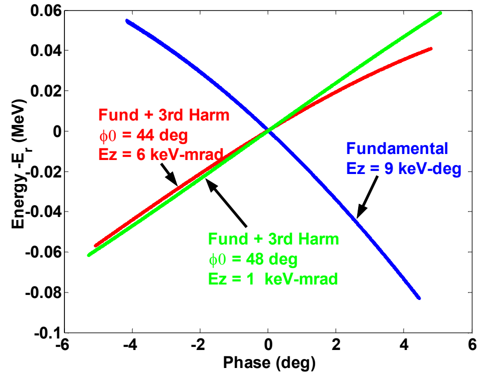

Figure 4. Longitudinal phase space with 0 nC of charge, 10 ps full width for fundamental only and fundamental + 3rd harmonic: E_0=82MV/m, E_3=-28MV/m, ϕ_3=15 degrees, ϕ_0 as shown.

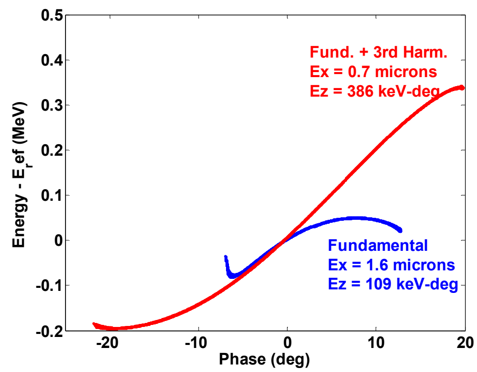

Figure 5. The 40 ps long bunch longitudinal phase space at 1 nC with and without the 3rd harmonic. For fundamental only: E_0=82MV/m, ϕ_0=20 degrees. For fundamental + harmonic: E_0=82MV/m, ϕ_0=35 degrees, E_3=-31.5MV/m, ϕ_3=17 degrees.

The results of both frequencies upon the emittance for a short, space charge dominated bunch is given in Figure 7. While the fundamental+3rd minimum projected emittance is not any lower than that with the fundamental alone. The beam quality is good over a wider range of injection phase, even indicating some improvement down to 10 degrees.

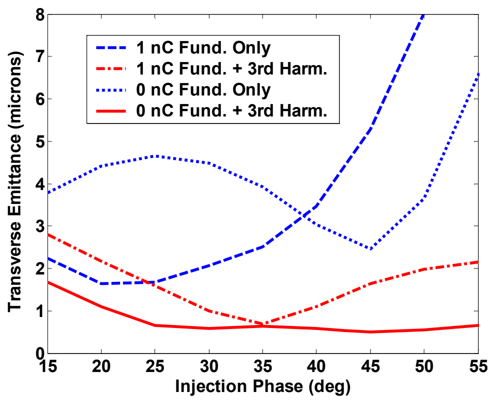

Figure 6. Transverse rf emittance for a 40 ps long square bunch. For 0 nC: E_0=82MV/m, ϕ_0=35 degrees, E_3=-28MV/m, ϕ_3=16 degrees. For 1 nC: E_0=82MV/m, ϕ_0=35 degrees, E_3=-31.5MV/m, ϕ_3=18 degrees.

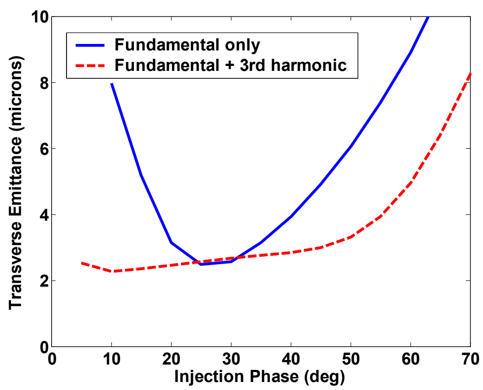

Figure 7. Short bunch transverse emittance for 1 nC at the exit of rf gun without and with the 3rd harmonic field: E_0=82MV/m, ϕ_0=25 degrees, E_3=-21MV/m, ϕ_3=17 degrees.

The reduction in the short bunch slice emittance is larger. Figure 8 gives the slice emittance plotted along the length of the bunch in degrees of rf and indicates that except for the head slices, the emittances are reduced from 0.6 to 0.3 microns or less over the main body of the bunch.

The configuration for and simulations results for the emittance compensation case are shown in Figure 9 for a 30 ps long, 1 nC bunch. The projected emittance equilibrates to 0.28 microns and the slices (not shown) are very well aligned with emittances of 0.2 microns over more than 95% of the bunch.

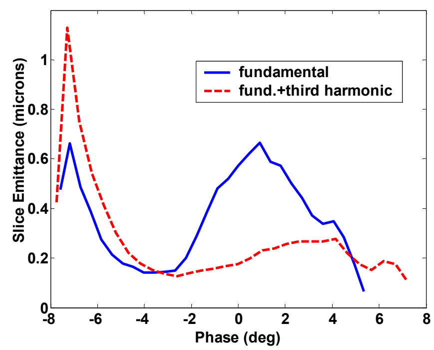

Figure 8. The short-bunch, slice emittance for 1 nC is plotted as a function of position along the bunch. The head of the bunch is to the left and 1 degree at s-band = 1.05 ps. E_0=82MV/m, ϕ_0=35 degrees, E_3=-21MV/m, ϕ_3=17 degrees.

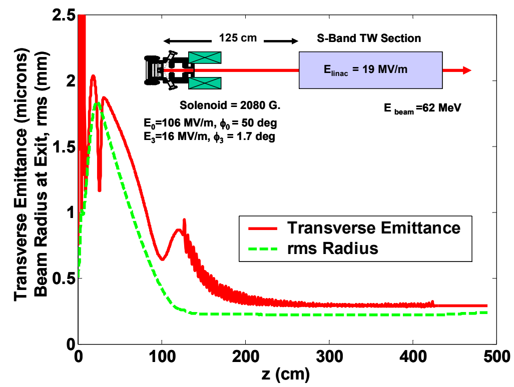

Figure 9. The projected transverse emittance and beam size of the two frequency gun with emittance compensation.

4. Acknowledgements

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5. References

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