SIMULATIONS OF HIGH-BRIGHTNESS RF PHOTOCATHODE GUNS FOR LLNL-SLAC-LBL 1 GeV TEST EXPERIMENT *

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Abstract

An ideal rf photocathode gun in a π-mode configuration supporting only a single mode with no nonlinear rf field is studied numerically with the simulation code PARMELA. For a given electron bunch, the normalized emittance can be minimized. Both the minimal normalized emittance and the optimized accelerating field are proportional to the square root of the peak current. Three possible rf photocathode guns for LLNL-SLAC-LBL 1 GeV test are simulated. The results show that both a 2 ps and a 6 ps half-width bunch with 8-17 mm-mrad emittance and 1 nC charge per bunch can be generated by guns with (1) f = 1269 MHz, E_o = 30 MV/m; (2) f = 1269 MHz, E_o = 60 MV/m; and (3) f = 2856 MHz, E_o = 60 MV/m. Here, f is the rf frequency, and E_o is the peak accelerating field.

Introduction

Relativistic klystrons are being developed as power sources to drive high gradient accelerators [1,2]. The next step is to demonstrate that a high gradient 1 GeV accelerator can be driven by a relativistic klystron. For this 1 GeV demonstration, a injector must provide a low emittance (8-30 mm-mrad), high peak current (300-600 A) electron beam within 15 degrees of rf phase ($\sim$ 3.5 ps) in a high gradient 11.4 GHz linac [3]. The Los Alamos photoinjector program [4, 5] has demonstrated that rf photocathode guns may satisfy this basic requirements. A preliminary physics design of a laser-driven photocathode rf gun has been completed at LBL [3].

We used the three-dimensional particle code PARMELA, modified by McDonald [6], to study beam dynamics in an rf field cavity. The photoelectrons are emitted with a profile determined by a laser pulse. The rf field used in PARMELA is the sum of several Fourier-Bessel components. To study optimization of the accelerating E field for the minimal emittance, we used only the fundamental Fourier-Bessel component such that there is no nonlinear rf field in the simulations. To study the possible rf photocathode guns for the 1 GeV test, we used the results of a SUPERFISH [7] calculation as coefficients of the Fourier-Bessel components. In all our simulations, the rf cavity consists of $2\frac{1}{2}$ cells (see Fig. 1). in which the first cell is a half cell. The second and the third cells are two identical full cells.

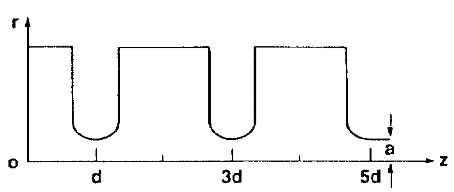

Fig. 1 Rf gun with a π-mode configuration.

Optimization of Gun Parameters

In general, the beam emittance increases in an rf photocathode gun due to several causes. One is the space charge effect which is dominant while the beam is nonrelativistic. This emittance growth can be reduced by increasing the accelerating field on and near the cathode and by shaping the radial profile of the laser pulse thus permitting control of the radial beam profile. The second factor is nonlinear external radial forces on the beam. However, one can carefully shape the walls of rf cavities to obtain the ideal linear transverse rf field [6]. The third factor is the time variations of the rf field over both the duration of the entire electron traveling time through the cavities and the duration of the entire electron bunch length.

For a Gaussian bunch such as the electron density takes the form $exp[-(x^2+y^2)/2\sigma_x^2](-\Delta z^2/2\sigma_z^2)$, Kim [8,9] has estimated the normalized emittance contributed by the rf field as

$$\epsilon_x^{rf} \approx \alpha k \sigma_x^2 (k\sigma_z)^2/\sqrt{2} \quad , \tag{1}$$

and contributed by the space charge effect as

$$\epsilon_x^{sc} = \frac{1}{\alpha k}\frac{\pi}{4}\frac{I}{I_A}\mu_x(A) \quad , \tag{2}$$

where $\mu_x(A) \approx (3A+5)^{-1}$, $\alpha = eE_o/2mc^2k$, k is the wave number of the rf field, m is the electron rest mass, c is the speed of light, E_o is the peak accelerating field, $A = \sigma_x/\sigma_z$ is the aspect ratio of the bunch, I is the peak current, and $I_A = 4\pi\varepsilon_o mc^3/e$ = 17 kA is the Alfvén current.

We can minimize the emittance by choosing the gun parameters. In general, a small laser spot σ_x is desirable to reduce beam emittance. The laser pulse length is somewhat limited by the bunches' phase spread in the linac. The charge or the peak current of a bunch is determined by the applications of the gun. For a given charge Q, Fig. 2 shows how the rf field strength and the pulse length change the normalized emittance. The simulation parameters are f = 1269 MHz, E_o = 40, 60, 80 and 100 MV/m, Q = 2 nC, σ_x = 3 mm, $\sigma_t = \sigma_z/c$=2-15 ps. The emitting phases are chosen to minimize the exit emittance. For a longer bunch, it has a smaller space charge induced emittance growth, and the emittance increase is dominated by the rf field contribution. On the other hand, the emittance increase in a short bunch is mainly due to the space charge forces. Hence, if a strong rf power is not available to control the space charge blow-up, one may use weak and long laser pulses to generate long electron bunches with a small peak current (but the same amount of charge in the bunch). Then, these bunches can be shortened with magnetic compressers.

For a bunch with a given peak current, both ϵ_x^{rf} and ϵ_x^{sc} increase as σ_z increases (see Eqs. (1-2)). A shorter laser pulse is favorable. However, generating very short laser pulses and tracking their photoemission effects are difficult techniques. Based on Eqs. (1-2), ϵ_x^{rf} is proportional to E_o, and ϵ_x^{sc} is inversely proportional to E_o. The net emittance is greater than the geometric sum and is less than the arithematic sum of these two emittance components. For a given I, we find that the emittance of a Gaussian bunch is at its minimum when the

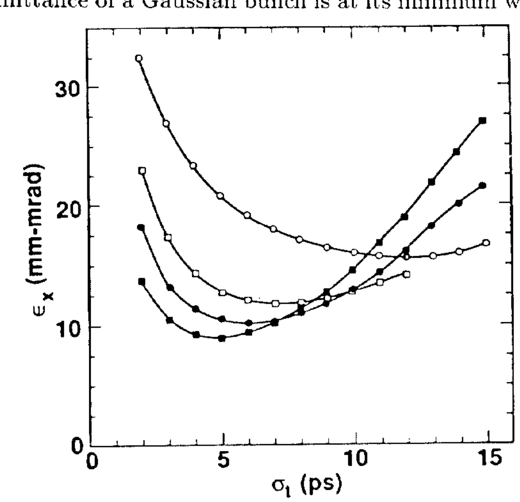

Fig. 2 The emittance as a function of the pulse length and the accelerating field E_o. The simulation parameters are f = 1269 MHz, Q = 2 nC, σ_x = 3 mm, and E_o = 40 (○), 60 (□), 80 (●) and 100 MV/m (■).

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peak accelerating field is given by

$$E_o = 2^{1/4}\frac{mc^2}{\epsilon}\left[\frac{\pi I}{I_A}\mu_x(A)\right]^{1/2} \Big/ \sigma_x k \sigma_z \quad . \qquad (3)$$

The minimized emittance is given by

$$\epsilon_{min} \approx 2^{-1/4}\sigma_x k \sigma_z \left[\frac{\pi I}{I_A}\mu_x(A)\right]^{1/2} \quad , \qquad (4)$$

and $\epsilon_x^{rf} = \epsilon_x^{sc}$. In Figs. 3(a) and 3(b), we plot the optimal E field (described in Eq. (3)) and the minimal emittance (given by Eq. (4)) as a function of rf frequency. In both figures, I=100 A, σ_x = 3 mm and σ_t = 2, 7, 12, 17 and 22 ps.

Figure 3a shows that a very strong field is needed to control the space charge blow-up in a short bunch. Note that the optimal field is inversely proportional to the frequency. Since the breakdown field is roughly proportional to the square root of the rf frequency [10], it is difficult to optimize the accelerating field at the low frequency without reaching the breakdown limit. The rf guns for short bunches are almost always operated in a region in which the space charge effects predominate regardless of the rf frequency, and the emittance is not at its minimum. For this reason, the main consideration in design of such rf guns is maximizing the accelerating field. For longer bunches, one can use the optimal field to obtain the minimal emittance, which is roughly linearly proportional to the bunch length. Therefore, the emittance per unit length is small and uniform.

Rf Photocathode Guns for 1 GeV Test

Two different frequencies (1269 MHz and 2856 MHz) are considered for our possible rf photocathode guns. As discussed earlier, to reduce the emittance growth in a short bunch one should minimize the nonlinear rf field and maximize the accelerating field on the cathode and along the accelerating axis of the gun. However, increasing the accelerating field indefinitely would eventually cause field emission from the cavity wall. Hence, a cavity with a small ratio of the peak surface field to the peak axial field is desirable. Therefore, the shunt impedance of the cavity should not be maximized. The gun configurations studied in this report are similar to the Brookhaven Accelerator Test Facility's gun geometry, which has little nonlinear rf field and a reasonable ratio (1.06) of the maximum surface field to the accelerating field on the cathode [6].

The parameters of our two and a half cells gun are given

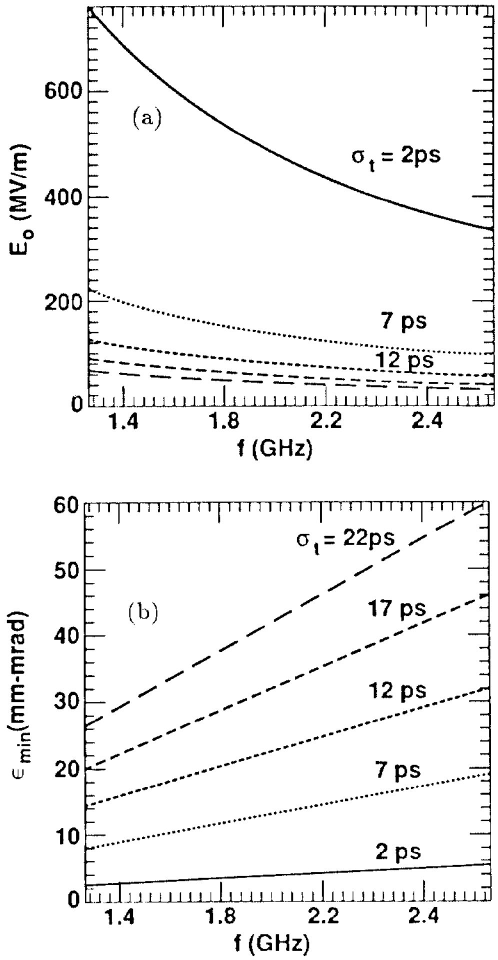

Fig. 3 (a) The optimal accelerating electric field and (b) the minimal normalized emittance for an electron bunch with a peak current I = 100 A and a radius σ_x = 3 mm as a function of the rf frequency and the bunch length.

Table I. Rf photocathode gun parameters

	Case 1		Case 2		Case 3	
Rf frequency (MHz)	1269		1269		2856	
First cell length (cm)	5.906		5.906		2.625	
Second cell length (cm)	11.812		11.812		5.250	
Third cell length (cm)	11.812		11.812		5.250	
Cell radius (cm)	9.130		9.130		4.160	
Aperture radius (cm)	1.5		1.5		1.0	
Iris radius (cm)	1.5		1.5		1.0	
Field on cathode (MV/m)	30		60		60	
Peak surface field (MV/m)	33.6		67.2		64.8	
Optimal injection phase ϕ_o	58°		70°		47°	
Laser spot radius[(a)] (mm)	3	3	3	3	3	3
Laser pulse half width[(a)] (ps)	2	6	2	6	2	6
Charge per bunch (nC)	1	1	1	1	1	1
Exit peak current[(b)] (A)	133	82	212	118	212	106
Emitting r.m.s. ϵ_x (mm-mrad)	0.56	0.56	0.56	0.56	0.56	0.56
Normalizedϵ_x at the exit (mm-mrad)	17.43	12.60	13.39	8.30	14.30	9.64
$\delta\epsilon_x/\epsilon_x$ due to 1 ps jitter (%)	20	4.4	20	8.5	11	0.5
Beam energy (MeV)	5.0	5.0	10.0	10.0	4.1	4.1
Energy jitter ($\times 10^{-4}$)	4	2	2	2	4	8
Energy spread $\Delta\gamma/\gamma$ (%)	0.7	0.6	0.3	0.2	0.5	0.3
Exit beam angular divergence x' (mrad)	8.8	8.3	6.0	5.3	13.4	12.1
Exit r.m.s. bunch radius (mm)	4.1	3.7	3.0	2.8	3.2	3.0
Exit r.m.s. bunch length (mm)	0.8	1.3	0.5	0.9	0.5	1.0

(a) for a uniform cylindrical laser pulse (b) assuming a Gaussian bunch in Table I. The cavity wall with the cathode is flat. Electron bunches are radially expanded near the cathode because of the space charge field. Whether shaping the cathode surface will compensate for the space charge effect without increasing the emittance growth from the rf field and without increasing the surface field on the wall still needs investigation. One can shape the laser pulse to improve the uniformity of the radial and longitudinal profiles. Unless mentioned otherwise, we obtained all simulation data presented in this section by assuming uniform laser pulses in both transverse and longitudinal directions. The total charge per bunch is 1 nC, and the bunch radius is 3 mm.

Nonlinearity of one rf gun (f = 1269 MHz and E_o = 30 MV/m) is checked by turning off the space charge fields in the PARMELA calculations. Figures 4(a) and 4(b) show results of using a linear rf field (marked with "□") and using the rf field calculated by SUPERFISH (marked with "Δ") for the gun described in Table I. The effect of the nonlinear rf field on the emittance is small. However, electrons gain more energy in the rf field calculated by SUPERFISH. Figure 4 also shows that the optimal injection phase ϕ_0 of the center of the laser pulse is 58° for these gun parameters.

To generate a 4 ps long bunch, we can use a 2 ps half width (Δz) laser pulse to generate an electron bunch. For $f = 1269$ MHz, $E_o = 30$ MV/m and $\phi_0 = 58°$, the space charge blowup is severe, and ϵ_x is 17.4 mm-mrad at the exit of the gun. Due to the macro-pulse jittering, the fluctuation in Δz is expected to be ± 1 ps. The emittance fluctuation due to the jitter is intolerable ($\sim$ 20%). The bunch energy is about 5 MeV with a 0.65% energy spread. The r.m.s. angular divergence is 9.3 mrad. The r.m.s. bunch length is 0.8 mm or 2.7 ps. Assuming that the exiting bunch's longitudinal profile is Gaussian, the peak current is about 133 Amp. The other option is to use longer pulses such as $\Delta z = 6$ ps and then to compress the bunches to a desired length. However, preserving the emittance during compression will take some care. For $\Delta z = 6$ ps, the space charge effect is weaker. Hence, ϵ_x (12.6 mm-mrad) and its fluctuation (4.4%) due to the jitter reduce. The r.m.s. bunch length is 1.3 mm or 4.3 ps. The simulation shows that the correlated energy spread at the exit is about three times of the uncorrelated spread. It is possible to compress the electron bunch by a factor of 3. Then, the final r.m.s. bunch length will be about 1.4 ps, and the peak current will be 250 A.

A summary of the simulation results is given in Table I. Cases 1 and 2 use the same rf frequency (1269 MHz) but different E_o (30 and 60 MV/m). Increasing E_o reduces the space charge effects, and, hence reduces the corresponding emittance growth, energy spread, and bunch size. Cases 2 and 3 have the same E_o (60 MV/m) but different rf frequencies (1269 and 2856 MHz). Therefore, ϵ_x^{sc} is roughly the same for both cases. However, ϵ_x^{rf} is larger for Case 3, so are the energy spread, beam divergence, and bunch size.

We have also studied the effects of laser pulse shape on emittance. Three different profiles (uniform in both r and z, uniform in r and Gaussian in z, and Gaussian in both r and z) are used in the simulations. The total laser power and the peak laser intensity of all these three profiles are the same. We find that the emittance is more sensitive to the shape of the laser pulse if the pulse length is short or if the rf field is weak. For Cases 1 and 2 in Table I, the emittance change due to different profiles is less then 30%. Since our guns are operating in the space charge dominating region, we find that the emittance increases roughly by a factor of 2 as the number of electrons in a bunch doubles.

Summary

We have obtained numerically both a 1.7-2.7 ps half-width bunch and a 3-4.3 ps half-width bunch with $\epsilon_x \approx$ 8-17 mm-mrad for (1) f = 1269 MHz, E_o = 30 MV/m; (2) f = 1269 MHz, E_o = 60 MV/m; and (3) f = 2856 MHz, E_o = 60 MV/m. The peak current is in the range of 130-210 A for the 1.7-2.7 ps bunch and 80-120 A for the 3-4.3 ps bunch. We can double the peak current by doubling the laser intensity. However, the emittance also increases by a factor of 2. Note that the rf field used in Case 2 is somewhat bound by the breakdown criterion because the maximal surface field on the cavity wall is about 67 MV/m, which is close to the L band's breakdown limit.

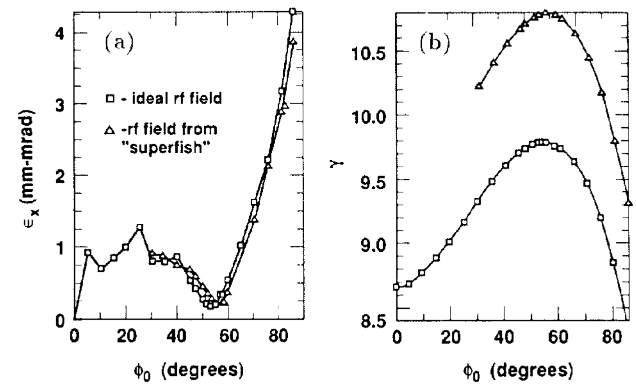

Fig. 4 Comparison of the rf field effects by using a linear rf field ("□") and a rf field calculated by SUPERFISH ("Δ") for a rf gun described in Table I, Case 1. (a) The emittance ϵ_x^{rf} and (b) the dimensionless electron energy γ versus the emitting rf phase ϕ_o are plotted.

Since the rf photocathode guns for short bunches are almost always operated in the space charge dominating region, it is desirable to have a stronger accelerating field. Therefore, the next practical question is how to build a rf cavity to support a larger field.

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