Design and Modeling of a 17 GHz Photocathode RF Gun

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Abstract

The performance of a high-frequency(17GHz), high accelerating gradient(250MV/m) photocathode RF gun is studied with the particle-in-cell code MAGIC. For the parameter regime of interest, i.e. bunch charge smaller than 1 nC and bunch length shorter than 2 ps, space-charge forces and finite bunch length effects are less significant in determining the beam quality than nonlinear RF forces are. The cavity geometry, RF phase for photoemission, cathode size, and current density are being optimized to obtain high quality beams. Preliminary results are presented.

1 INTRODUCTION

Future high-energy linear colliders and next generation free electron lasers require electron bunches with ultra-high brightness. The brightness achievable in conventional DC guns followed by RF bunchers have reached their intrinsic limitations and do not meet the stringent requirements set by future applications. Therefore, research on the generation of high brightness electron beams by photocathode RF guns has been very active in the last few years [1-8]. The operating frequencies of these systems range from 500 MHz to 3 GHz. In this paper, we present a design of a 17 GHz photocathode RF gun. Our design is based upon scaling the 2.856 GHz RF gun presently under test in Brookhaven National Laboratory (BNL) [1-3]. In spite of its technical difficulties and physics issues associated with high frequencies, the 17 GHz operation allows us to achieve high accelerating gradient, to make the system compact, to reduce space-charge forces, and to obtain high brightness beams. Furthermore, it can be directly integrated into subsequent accelerating structures operating at the same frequency. Also, it provides a chance to study high-frequency wakefield effects. It is very difficult, however, to achieve high bunch charge because of the small cathode and short bunch length. As a result, one is forced to resort to higher current densities and/or longer bunch lengths than a simple scaling of the BNL design would indicate. Furthermore, breakdown at 17 GHz has yet to be experimentally studied. Therefore, the peak accelerating gradient has to be carefully chosen to avoid breakdown.

In this paper, the mechanisms that can degrade beam quality, such as time-dependent RF effects, nonlinear RF forces, and space-charge forces, are studied in detail by using the particle-in-cell code MAGIC. The space-charge plays an unimportant role because of the high accelerating gradient. The beam quality is dominated by nonlinearities in RF fields. In Section 2, the design and simulation results are presented. A brief conclusion is given in Section 3.

2 DESIGN PHILOSOPHY AND RESULTS

The relation between RF gun design parameters and their related physics considerations are summarized in Table 1. The philosophy of our gun design is: (1) Choose the accelerating gradient according to available RF sources and breakdown limits. (2) Design the cavity geometry to reduce nonlinear RF forces. (3) Determine the laser pulse length and fix the RF phase for photoemission to optimize time-dependent RF effects. (4) Determine the cathode size and current density which minimize the emittance growth induced by nonlinearities in RF fields and space-charge forces.

If one extrapolates the data obtained at lower frequencies as measured by Wang [9], the breakdown field strength at 17 GHz should be around 800 MV/m. To keep the cavity surface field strength below the breakdown threshold, the peak accelerating gradient is chosen to be 250 MV/m, corresponding to a peak surface field smaller than 300 MV/m. These fields are achievable using power from a CARM(Cyclotron AutoResonance Maser) currently under development at MIT.

The TM modes of a cylindrically symmetrical cavity can be uniquely determined by $E_z(z,0)$, the electric field on the cavity axis[11]:

$$E_z(z,r) = E_z(z,0) - \frac{r^2}{4}f(z) + O((kr)^4) \qquad (1)$$

$$E_r(z,r) = -\frac{r}{2}\frac{d}{dz}E_z(z,0) - \frac{r^3}{16}f'(z) + O((kr)^5) \qquad (2)$$

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$$B_\phi(z,r) = \frac{kr}{2c}E_z(z,0) - \frac{kr^3}{16c}f(z) + O((kr)^5) \quad (3)$$

where

$$f(z) = (\frac{d^2}{dz^2} + k^2)E_z(z,0). \quad (4)$$

Therefore all nonlinear terms are proportional to $f(z)$ or $f'(z)$. McDonald[10] proposed the following ideal gun shape to make both $f(z)$ and $f'(z)$ identically zero

$$r = \sqrt{a^2 - (\frac{4d}{\pi})^2 \log(\sin\frac{\pi z}{2d})}, \quad (5)$$

where a is the aperture radius and d is the half cell length (i.e. a quarter wavelength). Unfortunately, this cavity shape is not realizable since it requires r to go to infinity as z approaches zero. We propose to follow the ideal shape as much as possible, and some improvements over the BNL design [1] have been observed. Also it is worth noting that near the exit of the second cell nonlinear RF forces are very significant [10]. There may be further improvements on the cavity shape around the exit. The final design is still under investigation.

The energy gain, energy spread, emittance, and final bunch length depend on the laser pulse length and the RF phase at which the laser pulse strikes the cathode. In our design the laser pulse length is chosen to be 1-2 ps. Given a laser pulse of $\tau_L = 1.4$ ps (corresponding to 8.5° in RF phase; the pulse length in space is defined as $\sigma_z \equiv \frac{\tau_L c}{2} = 0.21mm$), and a peak RF accelerating gradient of 250MV/m, the dependence of the energy gain, energy spread, emittance, and final bunch length (σ_z) on the RF phase at the center of the laser pulse have been obtained from MAGIC simulations. The results are summarized in Fig. 1 and 2. The final bunch length is roughly a linear function of the RF phase up to 45°. To achieve a shorter bunch length, the RF phase for photoemission is chosen to be 12°. Using this RF phase we achieve bunch compression from 1.4 ps to 0.52 ps, without substantial loss of beam quality.

Table 1: RF gun design considerations.

parameters		related physics
accelerating gradient		beam energy, breakdown
geometry	cathode shape	space charge forces
	aperture shape	nonlinear RF forces
laser	pulse length	bunch length effects
	RF phase	time-dependent RF effects
bunch charge	cathode size	nonlinear RF forces
	current density	space-charge forces

Table 2: Preliminary design parameters.

peak accelerating gradient	250MV/m
laser pulse length	1.4ps
final bunch length	0.52ps
RF phase for laser pulse	12°
current density	$6.7kA/cm^2$
cathode radius	0.5mm
bunch charge	0.1 nC
emittance	4π mm-mrad
energy spread	0.4%
current	192A
brightness	1.2×10^{12} $\frac{A}{(mrad)^2}$

After determining the cavity shape, the accelerating gradient, and the RF phase for photoemission, we choose the cathode radius and the current density. The interplay between the space-charge forces and nonlinearities in RF forces is studied by MAGIC using different combinations of current densities and cathode radii. The results are shown in Fig. 3, 4, and 5. It is clear that the emittance is dominated by the nonlinear RF forces, which grow as the radius becomes larger. In contrast, the space-charge forces, which increase as the current density becomes larger, are moderate. The energy spread is dominated by space-charge forces and is not a strong function of the cathode radius. While it may seem that the energy spread is very large as the current density increases, longitudinal phase-space plots (not shown) indicate that momentum is correlated with position. Thus the momentum spread can be corrected by using focusing techniques. By using $J = 67kA/cm^2$ with a cathode radius of 0.5mm, we are able to achieve 1nC per bunch with an emittance of 7π mm-mrad.

3 CONCLUSION

The electron beam dynamics in our 17 GHz RF gun are investigated numerically. Space-charge forces and finite bunch length effects are found to be moderate compared to nonlinear RF forces. Bunch compression due to natural RF phase focusing can be obtained by proper choice of the RF phase for photo-emission. Electron bunches of 2.3 MeV/c momentum, 0.52ps width, and 1 nC charge with 7π mm-mrad emittance are obtained. The gun performance is dominated by nonlinear RF forces, hence future efforts should be made towards improving the cavity aperture design to further reduce nonlinear RF forces. The preliminary design results are summarized in Table 2.

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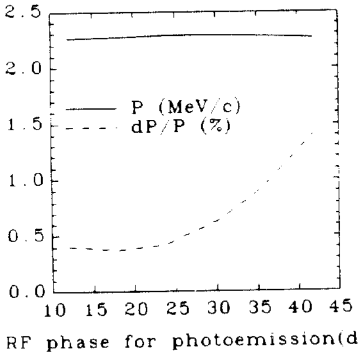

Figure 1: Momentum and momentum spread as a function of the RF phase at the center of laser pulse.

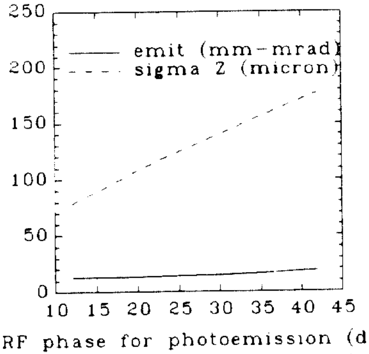

Figure 2: Emittance and bunch length (σ_z) as a function of the RF phase at the center of laser pulse.

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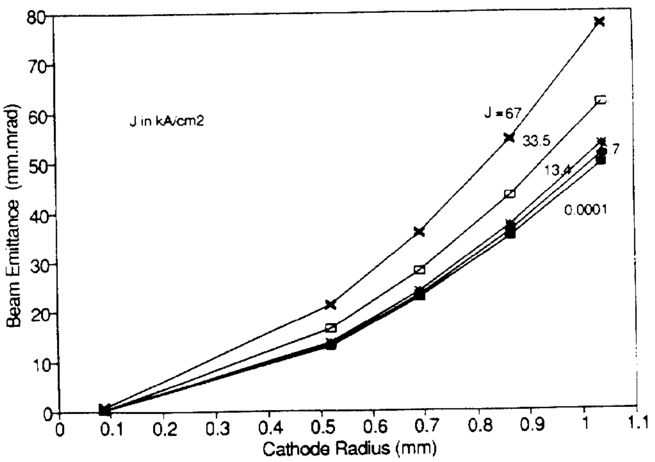

Figure 3: Emittance as a function of cathode radius under different current densities.

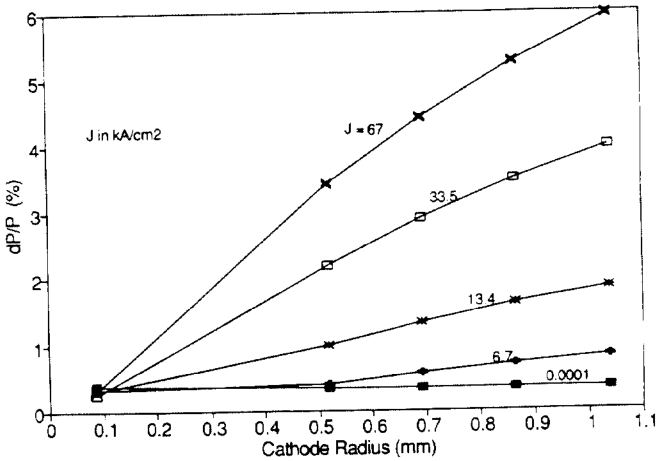

Figure 4: Momentum spread as a function of cathode radius under different current densities.

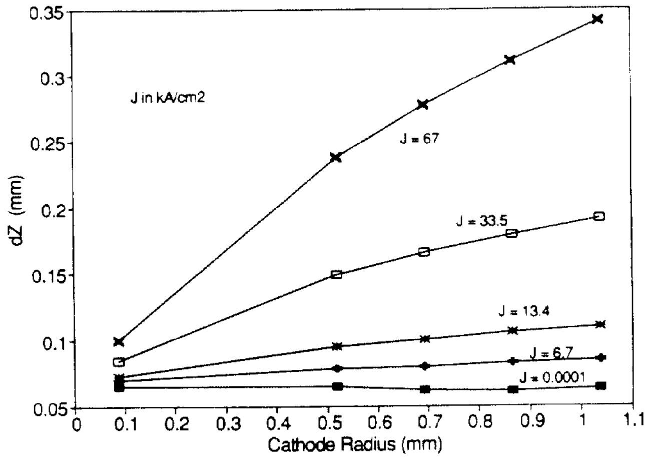

Figure 5: Bunch length (σ_z) as a function of cathode radius under different current densities.