EFFECT OF RF GRADIENT UPON THE PERFORMANCE OF THE WISCONSIN SRF ELECTRON GUN*

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Abstract

The performance of the Wisconsin 200-MHz SRF electron gun is simulated for several values of the RF gradient. Bunches with charge of 200 pC are modeled for the case where emittance compensation is completed during post-acceleration to 85 MeV in a TESLA module. We first perform simulations in which the initial bunch radius is optimal for the design gradient of 41 MV/m. We then optimize the radius as a function of RF gradient to improve the performance for low gradients.

INTRODUCTION

A superconducting radiofrequency (SRF) electron gun has been designed and constructed to produce 200-pC bunches that are suitable for a high-repetition-rate (5 MHz) soft-xray free electron laser (FEL) [1–5]. Bunches are created by laser illumination of a photocathode and then accelerated to an energy of 4 MeV by a 200-MHz SRF cavity with peak electric field of 41 MV/m on the cathode. The electron gun utilizes a Cu photocathode, which can be replaced with a Cs_2Te photocathode whose higher quantum efficiency allows operation with lower laser power.

When a bunch is accelerated and compressed to achieve a peak current of ~1 kA for an FEL, current and energy modulations can cause microbunching that spoils the FEL process [1]. To minimize modulations in longitudinal phase space at the expense of slightly increased transverse emittance, “blowout” mode is employed, in which the initial bunch length is small compared to that of the accelerated bunch [6]. Simulations of blowout mode show that longitudinal and transverse modulations of the initial bunch distribution emitted from the photocathode are smoothed out by the self field space charge force [3].

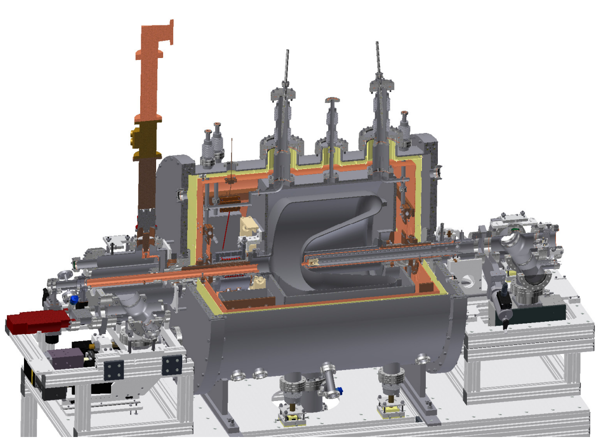

Figure 1: The photocathode, SRF cavity and high-temperature superconducting solenoid in the liquid-helium cryostat. Courtesy of G. C. Rogers.

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We study the gun performance with simulations that include emittance compensation [7] from focusing the bunches in a high-temperature superconducting (HTS) solenoid [8] that is immediately downstream of the SRF cavity, and then accelerating them to 85 MeV in a cryomodule containing eight TESLA 1.3-GHz SRF cavities. The first TESLA cavity is used as a buncher, with the phase and gradient adjusted to control transverse focusing. The bunches become longitudinally frozen after travelling 3 m and reaching an energy of 6 MeV. For the design gradient of 41 MV/m, simulations indicate that bunches with normalized emittance of ~1 mm-mrad emerge from the cryomodule [5]. Figure 1 shows the photocathode, SRF cavity, and solenoid in the liquid-He-cooled cryostat.

In this article, we evaluate the production of 200-pC bunches when the peak electric field on the cathode of the 200-MHz cavity differs from the design gradient of 41 MV/m. The ASTRA [9] code is used to perform 100,000-particle simulations of a realistic bunch that initially has truncated Gaussian radial and longitudinal profiles, truncated at 0.8σ. (Note that for a Gaussian profile truncated at 0.8σ, σ is not the rms value.) For the Wisconsin electron gun, previous studies [5] have shown agreement between ASTRA simulations and simulations performed with the GPT code [10].

An initial longitudinal σ of 187.5 fs is studied; nearly identical results have been obtained with smaller values of the longitudinal σ, consistent with blowout mode. Since the electron velocity depends upon the RF gradient, we use the AUTOPHASE feature of the ASTRA code to set the RF phase when a bunch enters a TESLA cavity to equal the optimized phase for the design RF gradient of 41 MV/m.

A bunch is emitted from a Cu or Cs_2Te photocathode with initial transverse normalized slice emittances ε_x and ε_y that are related to the rms laser spot dimensions by $\varepsilon_{x,y}$ [mm-mrad] ≈ $\sigma_{x,y}$ [mm], and initial kinetic energy of ~0.5 eV [11, 12]. For a Gaussian radial profile truncated at $0.8\sigma_r$, the rms dimensions are given by $\sigma_{x,y} = 0.4\sigma_r$.

FIXED BUNCH RADIUS

We first considered the initial bunch radius that gives the lowest output emittance for the design gradient of 41 MV/m. For a truncated Gaussian radial profile truncated at $0.8\sigma_r$, this initial radius σ_r is 1.75 mm [5]. The rms

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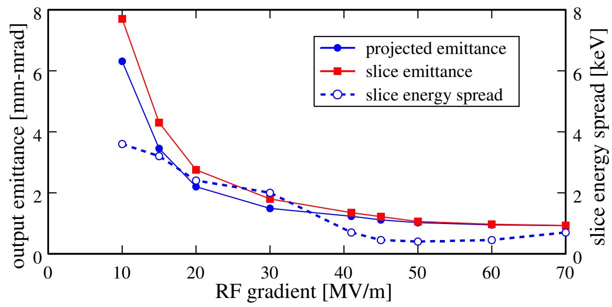

Figure 2: Bunch properties versus peak RF gradient, for a truncated Gaussian bunch distribution emitted from a Cu or Cs_2Te photocathode, with initial radial σ_r of 1.75 mm, initial longitudinal σ of 187.5 fs, and initial emittance of 0.7 mm-mrad. The focusing strength of the solenoid was optimized for each value of the RF gradient, in order to minimize the projected emittance. The normalized projected and slice emittances, and the slice energy spread, are evaluated at the exit of the TESLA module where the beam energy is 85 MeV.

bunch dimensions are $\sigma_{x,y}$ = 0.7 mm, so for a Cu or Cs_2Te photocathode, we assume that the initial normalized slice emittances are $\varepsilon_{x,y}$ = 0.7 mm-mrad. For the design gradient, the lowest projected emittance at the exit of the TESLA module is obtained when the longitudinal integral of the square of the solenoidal magnetic field, $\int B^2 dz$, equals 31.1 kG^2-cm. For this case, the normalized projected and slice emittances are 1.3 mm-mrad, the slice energy spread is 0.7 keV, and the peak current is 35 A.

For each value of the peak RF gradient that we studied, the solenoid field strength was optimized to obtain the lowest projected emittance at the exit of the TESLA module. Figure 2 shows the projected emittance of the bunch, and the slice emittance and slice energy spread in the longitudinal center of the bunch. To evaluate the slice properties, 200 slices—each containing 500 particles—were considered. Since the slice emittance is largest near the bunch center, it is possible for the projected emittance to be smaller than the slice emittance of the center slice. While the output emittances decrease with increasing RF gradient, the slice energy spread reaches a minimum value of 0.4 keV when the RF gradient is 50 MV/m.

OPTIMIZED BUNCH RADIUS

When the RF gradient is lower than the design value of 41 MV/m, the space-charge-induced emittance growth is increased for a given bunch radius. Consequently, the initial bunch radius that produces the smallest output emittance depends upon the RF gradient. We performed simulations in which the initial bunch radius and solenoid field strength were both optimized to obtain the smallest projected emittance for each value of the RF gradient, for a Cu or Cs_2Te photocathode with initial $\varepsilon_{x,y}$ [mm-mrad] = $\sigma_{x,y}$ [mm]. The results in Fig. 3(a) show that optimizing the initial bunch radius significantly improves the performance for RF gradients lower than the design value. The output emittances decrease with increasing RF

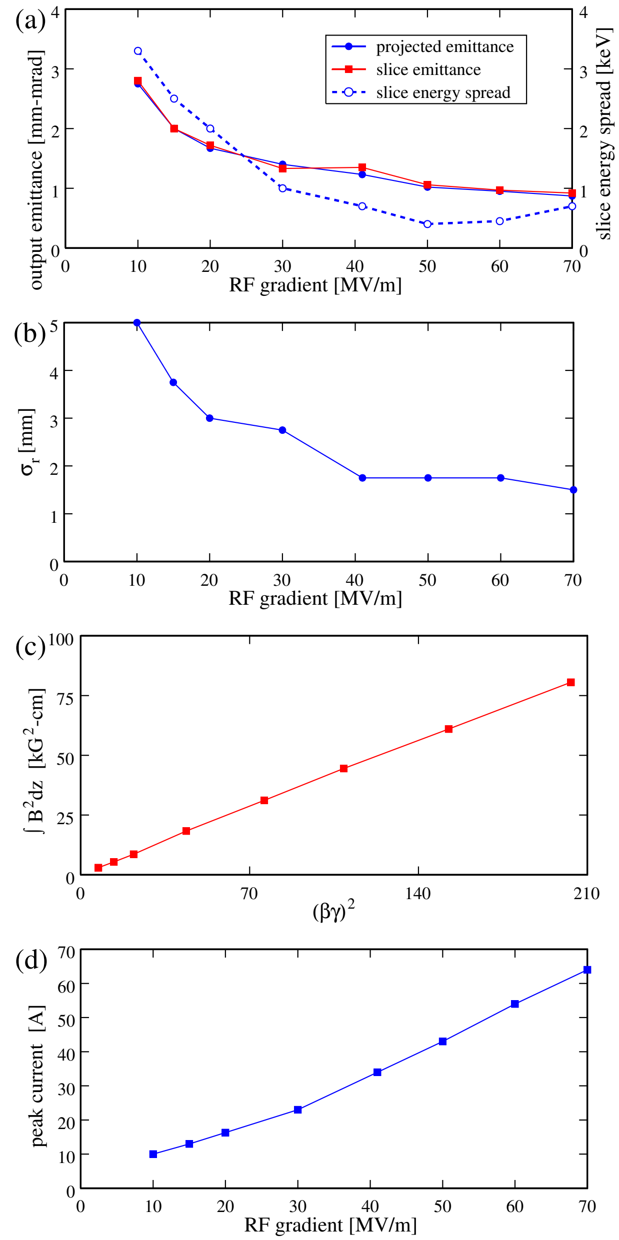

Figure 3: Bunch properties vs. peak RF gradient. The initial bunch radius and the solenoidal field are optimized for each value of the gradient to minimize the projected emittance for a Cu or Cs_2Te photocathode. (a) The normalized projected and slice emittances and slice energy spread at the exit of the TESLA module. (b) The optimal value of σ_r vs. RF gradient, for a Gaussian radial distribution truncated at $0.8\sigma_r$. (c) The integral of the square of the optimized solenoidal field, $\int B_z^2 dz$, vs. the bunch's $(\beta\gamma)^2$ in the solenoid. (d) Peak current at the exit of the TESLA module.

gradient, while the energy spread is minimized at 0.4 keV for a peak gradient of ~50 MV/m.

Figure 3(b) shows the optimal value of σ_r as a function of the RF gradient. For lower RF gradients, it is advantageous to have a larger initial radius, even though the initial emittance from the photocathode is increased.

For the RF gradients studied, Fig. 3(c) shows that the longitudinal integral of the square of the solenoidal magnetic field, $\int B^2 dz$, is proportional to the bunch's $(\beta\gamma)^2$ in the solenoid, where β is the electron velocity divided by the speed of light, and γ is the relativistic factor. This indicates that the optimized focal length of the solenoid is independent of the RF gradient.

Neglecting space charge effects, the focal length of the solenoid, *f*, in the thin-lens approximation, obeys [13]

$$\frac{1}{f} = \left(\frac{e^2}{4m^2c^2}\right)\frac{\int B^2 dz}{(\beta\gamma)^2}\ , \qquad (1)$$

where *e* is the electron charge, *m* is the electron mass, and *c* is the speed of light.

For the optimal solenoidal field strength, the calculated focal length is 0.29 m for all values of the RF gradient. The image of the cathode is located near to the entrance of the second RF cavity in the 8-cavity TESLA module, whose first RF cavity has phase and gradient adjusted for use as a buncher. The location of the cathode's image is consistent with the emittance compensation process, in which a beam waist is formed near to the entrance of the first RF cavity that is used for acceleration of the beam [1, 7].

Figure 3(d) shows the bunch's peak current at the exit of the TESLA module. The peak current increases with RF gradient because of decreasing longitudinal expansion due to space charge.

For simulations in which the initial bunch has a truncated Gaussian profile, a gradient of 15 MV/m is sufficient to produce a high-quality bunch with normalized transverse emittance of 2 mm-mrad, slice energy spread of 2.5 keV, and peak current of 13 A. For the design value of the gradient, 41 MV/m, a bunch is produced with normalized transverse emittance of 1.3 mm-mrad, slice energy spread of 0.7 keV, and peak current of 35 A. With a slightly larger gradient of 50 MV/m, the slice energy spread decreases to 0.4 keV, while the normalized emittance is 1 mm-mrad and the peak current is 43 A. For gradients exceeding 55 MV/m, the peak current exceeds 50 A.

SUMMARY

For the Wisconsin SRF electron gun, simulations have been performed to study the dependence of the output bunch properties upon the peak RF gradient on the cathode of the 200-MHz cavity. To model realistic bunches from laser illumination of a photocathode, we simulated bunches whose initial radial and longitudinal profiles are truncated Gaussian distributions, truncated at 0.8σ. To minimize the output emittance, we optimized the initial bunch radius and field strength of the emittance-compensation solenoid for each value of the RF gradient. For gradients of 10–70 MV/m, the output emittance decreases and the peak current increases with increasing gradient, while the slice energy spread is minimized at 0.4 keV for a gradient of 50 MV/m. For gradients exceeding 50 MV/m, the normalized output emittance is smaller than 1 mm-mrad, and for gradients exceeding 55 MV/m, the peak current exceeds 50 A.

For gradients exceeding 15 MV/m, the 200-pC bunches have normalized slice and projected emittances smaller than 2 mm-mrad, slice energy spreads smaller than 2.5 keV, and peak currents exceeding 13 A. These bunches are suitable for a soft xray FEL.

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