MINIMIZING EFFECTIVE SLICE ENERGY SPREAD IN A PHOTOCATHODE RF GUN FOR ULTRASHORT ELECTRON BUNCH GENERATION*

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Abstract

Effective slice energy spread is a key beam-quality parameter that limits the compression of ultrashort electron bunches. To suppress the RF-dominated growth of the effective slice energy spread in a photocathode RF gun, a 2.3–2.3 cell configuration with a cascaded cavity with a decelerating field is proposed on the basis of the quasi-DC 2.3-cell X-band gun. Simulations show that, without space-charge effects, the effective slice energy spread can be reduced from 121 eV to 37 eV, and further to 5 eV after field-ratio optimization. However, at high bunch charge, the compensation capability of the proposed scheme is limited by the nonlinear effects of space charge and related beam-dynamics effects. These results demonstrate that a cascaded cavity with a decelerating field provides an effective approach for suppressing RF-dominated effective slice energy spread in ultrashort-bunch RF guns.

INTRODUCTION

Ultrashort electron bunches are of great interest in free-electron lasers, ultrafast electron diffraction (UED), and advanced radiation sources [1]. In these applications, the residual energy spread that remains after removing the linear energy–time correlation, referred to here as the effective slice energy spread, is a key parameter that determines both the compression limit and the longitudinal beam quality. Under the condition of ideal linear compression, the minimum achievable bunch length is approximately given by

$$\sigma_{t,\min} \approx \frac{\sigma_{\delta,\mathrm{eff}}}{|h|}, \tag{1}$$

where $\sigma_{\delta,\mathrm{eff}}$ is the relative effective slice energy spread and $h = d\delta/dt$ is the linear energy chirp. Although magnetic compression, velocity bunching, and harmonic linearization can substantially improve bunch compression, the final pulse duration is ultimately limited by the effective slice energy spread once the compression process approaches the ideal linear regime [2]. Reducing the effective slice energy spread directly at the source is therefore essential for generating even shorter electron bunches.

Photocathode RF guns, as the core electron sources for modern advanced particle accelerator facilities, leverage exceptionally high accelerating gradients to rapidly accelerate photoelectrons to relativistic energies over extremely short distances. This capability effectively shortens the low-energy regime, thereby suppressing beam quality degradation induced by space-charge effects. Consequently, these guns can produce high-brightness electron beams characterized by both low emittance and high peak currents, establishing them as one of the most critical electron sources in advanced accelerator technology [3, 4]. Given their significant advantages in high-quality beam generation, the photocathode RF gun is selected as the research focus of this work to construct a high-performance electron beam generation system. Inspired by the quasi-DC behavior of the 2.3-cell X-band gun [5], a compensation scheme employing a cascaded cavity with a decelerating field is proposed to suppress the RF-dominated growth of the effective slice energy spread. The compensation mechanism, its sensitivity to initial beam parameters, and its applicability under space-charge effects are analyzed in the following sections.

DESCRIPTION OF EFFECTIVE SLICE ENERGY SPREAD AND COMPENSATION SCHEME

Let t denote the arrival-time deviation with respect to a reference particle, and let ΔE_z denote the longitudinal energy deviation. The second-order moments of the longitudinal phase space are represented by the covariance matrix

$$\Sigma = \begin{pmatrix} \sigma_{55} & \sigma_{56} \\ \sigma_{56} & \sigma_{66} \end{pmatrix}, \tag{2}$$

where $\sigma_{55} = \langle t^2 \rangle$, $\sigma_{66} = \langle \Delta E_z^2 \rangle$, and $\sigma_{56} = \langle t \Delta E_z \rangle$. The effective slice energy spread is then given by

$$\sigma_{E,\mathrm{eff}}^2 = \sigma_{66} - \frac{\sigma_{56}^2}{\sigma_{55}}, \tag{3}$$

which corresponds to the residual energy spread after removing the linear time–energy correlation. The corresponding relative effective slice energy spread is defined as $\sigma_{\delta,\mathrm{eff}} = \sigma_{E,\mathrm{eff}}/\langle E \rangle$, where $\langle E \rangle$ is the mean beam energy.

In a photocathode RF gun, the effective slice energy spread can originate from thermal emission, RF-field effects, and space-charge effects. Owing to the low initial emittance and small intrinsic energy spread of photoemission, the thermal-emission contribution is negligible compared with the RF-field and space-charge contributions. The simulations are performed for an X-band RF gun operating at

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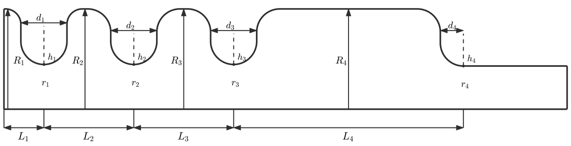

Figure 1: Schematic geometry of the proposed 2.3–2.3 cell photocathode RF gun.

11.424 GHz with a peak on-axis accelerating gradient of 190 MV/m.

To clarify the RF-induced effective-slice-energy-spread evolution, the following analysis is carried out without space-charge effects. In this case, the longitudinal accelerating field has a radial dependence approximately described by $J_0(kr)$. Therefore, particles near the axis and off axis within the same temporal slice experience different axial accelerating fields and gain different energies. In addition to this radial RF non-uniformity, phase slippage, longitudinal RF curvature, and transverse–longitudinal coupling can also contribute to the residual energy spread. For the ultrashort bunches considered here, the dominant RF contribution is the slice-internal radial energy difference driven by the transverse dependence of the axial RF field.

Since the 2.3-cell X-band RF gun exhibits excellent quasi-DC behavior and is especially suitable for ultrashort bunch generation [5], a 2.3–2.3 cell configuration is proposed by adding a cavity with a decelerating field after the original 2.3-cell gun, as shown in Fig. 1. Because the downstream cavity exhibits a similar $J_0(kr)$-type radial dependence and operates in a decelerating, defocusing regime, particles that gain more energy in the upstream accelerating section experience a stronger decelerating field downstream. In addition, the defocusing effect increases the transverse beam size, so that the particles sample a larger radial field difference in the decelerating section than in the upstream accelerating section. In this way, the radial energy difference accumulated in the accelerating section can be directly compensated, while the favorable quasi-DC operating characteristics of the original 2.3-cell RF gun are preserved around the target phase.

SIMULATION RESULTS AND DISCUSSION

Under the baseline condition without space-charge effects, the effective slice energy spread at the exit of the original 2.3-cell gun is about 121 eV. For the proposed 2.3–2.3 cell structure at the baseline field ratio of $R_E = 1$, it is reduced to 37 eV, corresponding to a reduction of about 70% in the effective slice energy spread. The evolution of the total beam energy along the gun is shown in Fig. 3. The output beam energy changes only slightly from 3.51 MeV to 3.37 MeV, indicating that the reduction of the effective slice energy spread is not accompanied by a severe loss of beam energy.

Fig. 2 compares the original 2.3-cell gun with the proposed 2.3–2.3 cell structure. The proposed configuration exhibits a much smaller longitudinal phase-space spread at the gun exit, demonstrating that the cascaded cavity can effectively compensate the slice-internal energy difference accumulated in the upstream accelerating section.

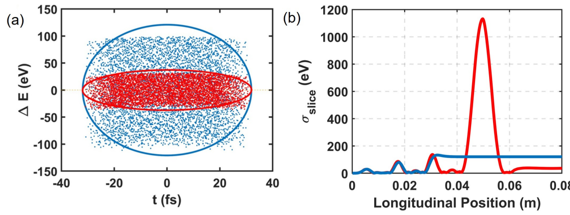

Figure 2: Comparison between the original 2.3-cell gun and the proposed 2.3–2.3 cell structure. (a) Longitudinal phase space at the gun exit. (b) Evolution of the effective slice energy spread along the gun. Blue: original 2.3-cell gun; red: proposed 2.3–2.3 cell structure.

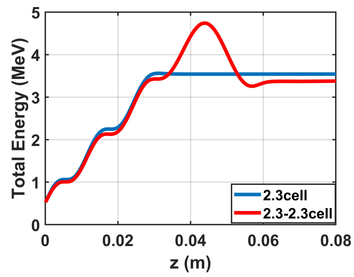

Figure 3: Total beam energy evolution.

To further clarify the radial compensation mechanism, single-particle tracking is performed for particles with different initial radial positions in the proposed 2.3–2.3 cell structure. The radial-position difference and the longitudinal-energy difference are evaluated with respect to the on-axis particle, as shown in Fig. 4.

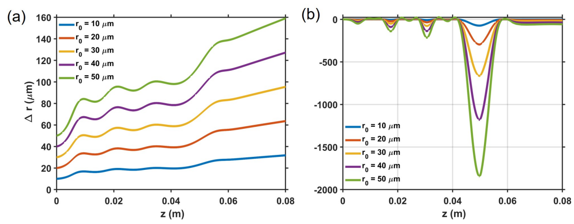

Figure 4: Single-particle tracking results for particles with initial radial positions from 10 to 50 μm in the proposed 2.3–2.3 cell structure. (a) Evolution of the radial-position difference relative to the on-axis particle. (b) Evolution of the longitudinal-energy difference relative to the on-axis particle.

Fig. 4(a) shows that particles with larger initial radial positions move further away from the axis as they propagate through the downstream section. This transverse expansion is enhanced in the decelerating region because the beam experiences a defocusing effect. As a result, off-axis particles sample a stronger radial variation of the axial RF field in the downstream cavity. Fig. 4(b) shows the corresponding longitudinal-energy difference relative to the on-axis particle. The off-axis particles experience a much stronger decelerating field in the downstream section, and the magnitude of the longitudinal-energy difference increases with the initial radial position. These results confirm that the radial energy difference accumulated in the upstream accelerating section can be directly compensated by the downstream decelerating cavity. Therefore, the reduction of the effective slice energy spread mainly originates from the enhanced radial compensation in the decelerating and defocusing section.

To explore the compression limit of the effective slice energy spread under this field profile, the field strength of the last cell is gradually increased while the field ratio among the first three cells is kept at 1. Here, R_E denotes the field-strength ratio of the last cell to the first three cells. The optimum compensation occurs at $R_E = 1.35$, where the minimum effective slice energy spread reaches 5 eV, corresponding to a reduction of about 96% relative to the original 2.3-cell structure. This indicates that an ultralow effective slice energy spread can be achieved only when the compensation strength of the cavity with a decelerating field is well matched to the energy distortion accumulated in the upstream section. A weaker decelerating field leads to under-compensation, whereas an excessively strong one introduces a reverse distortion.

The sensitivity of the proposed scheme to the initial beam parameters is further evaluated, as shown in Fig. 5. Fig. 5(a) shows that, compared with the original 2.3-cell gun, the 2.3–2.3 cell structure provides substantially better suppression of the effective slice energy spread over the full range of initial laser spot radii. In particular, the optimized case with $R_E = 1.35$ maintains a very low effective slice energy spread even at large spot sizes. Fig. 5(b) further shows that the proposed structure preserves a much lower effective slice energy spread than the original 2.3-cell gun over the scanned bunch-length range. These results indicate that the proposed configuration not only suppresses the effective slice energy spread effectively, but also maintains good tolerance to variations in the initial beam parameters.

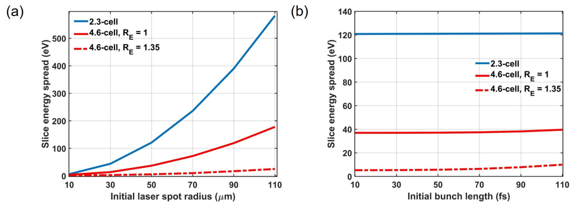

Figure 5: Effective slice energy spread versus initial beam parameters. (a) Initial laser spot radius. (b) Initial bunch length. Blue: original 2.3-cell gun; red solid: 2.3–2.3 cell structure with $R_E = 1$; red dashed: 2.3–2.3 cell structure with $R_E = 1.35$.

APPLICABILITY UNDER SPACE-CHARGE EFFECTS

To evaluate the applicability of the proposed structure under more realistic conditions, the dependence of the effective slice energy spread on bunch charge is examined for a fixed incident laser radius of 50 μm and an initial bunch length of 50 fs. The scheme remains effective at low bunch charge, whereas its compensation capability gradually degrades as the bunch charge increases. Specifically, at 1 fC, the cavity with a decelerating field reduces the effective slice energy spread from 129 eV to 44 eV; at 5 fC, from 170 eV to 100 eV; and at 10 fC, from 234 eV to 174 eV. These results indicate that the compensation benefit decreases significantly with increasing bunch charge.

This behavior is mainly attributed to nonlinear space-charge effects and the associated beam-dynamics evolution at high bunch charge [6, 7]. The longitudinal space-charge field becomes strongly nonlinear near the bunch head and tail, while the transverse space-charge force drives bunch expansion and enhances the sampling of the radial RF non-uniformity. More importantly, the longitudinal space-charge field acts in opposite directions on slice-internal particles at the bunch head and tail: in the head region, it adds constructively to the RF contribution and increases the effective slice energy spread, whereas in the tail region it partially cancels the RF contribution and reduces the effective slice energy spread. Because this distortion is strongly asymmetric along the bunch, a single cavity with a decelerating field cannot provide optimal compensation over the entire bunch. As a result, the overall compensation capability decreases progressively as the bunch charge increases.

CONCLUSION

A 2.3–2.3 cell configuration with a cascaded cavity with a decelerating field is proposed to suppress the effective slice energy spread of ultrashort electron bunches. The proposed structure reduces the effective slice energy spread from 121 eV in the original 2.3-cell gun to 37 eV, and further to 5 eV after field-ratio optimization. This reduction is mainly attributed to the enhanced radial compensation in the downstream decelerating and defocusing section, while the quasi-DC operating characteristics of the original gun are preserved. In the low-charge regime, the proposed scheme also maintains good tolerance to variations in the initial beam parameters. At high bunch charge, however, its compensation capability becomes limited. These results demonstrate that a cascaded cavity with a decelerating field provides an effective compensation scheme for RF-dominated effective-slice-energy-spread growth and a promising route toward ultrashort-bunch RF guns with reduced residual energy spread.

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