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

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Abstract

Slice energy spread is a key beam-quality parameter that limits the compression of ultrashort electron bunches. To suppress the RF-dominated slice-energy-spread growth 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 slice energy spread can be reduced from 121 eV to 37 eV, and further to 5 eV after field-ratio optimization. The proposed scheme also exhibits good tolerance to variations in the initial beam parameters, although its compensation capability at high bunch charge is limited by nonlinear space-charge effects. These results demonstrate that the cavity with a decelerating field provides an effective approach for the development of low-slice-energy-spread RF guns for ultrashort bunch generation.

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 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

$$\sigma_{t,\min} \approx \frac{\sigma_{\delta,\text{slice}}}{|h|}, \tag{1}$$

where $\sigma_{\delta,\text{slice}}$ is the relative 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 slice energy spread once the compression process approaches the ideal linear regime [2]. Reducing the 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 slice-energy-spread growth. The compensation mechanism, its sensitivity to initial beam parameters, and its applicability under space-charge effects are analyzed in the following sections.

DESCRIPTION OF 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 slice energy spread is then given by

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

which corresponds to the uncorrelated energy spread after removing the linear time–energy correlation.

In a photocathode RF gun, the slice energy spread mainly originates from thermal emission, RF-field effects, and space-charge effects. The contribution from thermal emission is estimated to be much smaller than those induced by RF-field and space-charge effects, indicating that it is not the dominant source of slice energy spread but mainly defines its physical lower limit.

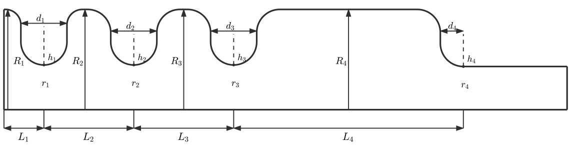

Figure 1: Schematic geometry of the proposed 2.3–2.3 cell photocathode RF gun.

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To clarify the RF-induced slice-energy-spread evolution, the following analysis is carried out without space-charge effects. In this case, the longitudinal accelerating field follows a radial dependence of $J_0(kr)$, so particles at different radial positions within the same temporal slice gain different energies, thereby generating slice-internal energy spread.

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 this cavity exhibits the same $J_0(kr)$-type radial dependence, particles that gain more energy upstream experience stronger deceleration downstream. In this way, the radial energy difference accumulated in the accelerating section can be directly compensated while preserving the favorable quasi-DC operating characteristics of the original 2.3-cell RF gun around the target phase.

SIMULATION RESULTS AND DISCUSSION

Under the baseline condition without space-charge effects, the slice energy spread at the exit of the original 2.3-cell gun is about 121 eV. For the proposed 4.6-cell structure at the baseline field ratio of $R_E = 1$, it can be reduced to 37 eV while keeping the average output energy nearly unchanged, corresponding to a reduction of about 70 %.

Figure 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 and a clear compensation stage in the downstream section. This demonstrates that the cascaded cavity with a decelerating field effectively compensates the slice-internal energy difference accumulated in the upstream accelerating section.

To clarify the origin of the compensation, the RF-induced slice-energy-spread evolution is analyzed from two aspects: the spatial dimension, corresponding to the radial RF non-uniformity for particles starting at different radial positions, and the temporal dimension, corresponding to the RF phase difference for particles emitted at different times. Based on this decomposition, single-particle tracking is used for the proposed configuration, and the results are shown in Fig. 3.

The results show that the slice-energy-spread evolution is strongly non-monotonic once the bunch enters the cascaded cavity with a decelerating field. In the rising part of the decelerating field, the spatial field profile tends to compensate the radial energy difference introduced by the upstream RF non-uniformity, since on-axis particles experience stronger deceleration. At the same time, phase slippage in the temporal dimension opposes this compensation and causes a temporary increase in the slice energy spread. As the bunch propagates further into the falling part of the decelerating field, the temporal effect reverses and produces strong phase focusing. Meanwhile, the transverse bunch size increases in the decelerating region, enhancing the sampling of the radial field difference. The combined action of temporal phase focusing and spatial radial compensation ultimately reduces the exit slice energy spread to 37 eV.

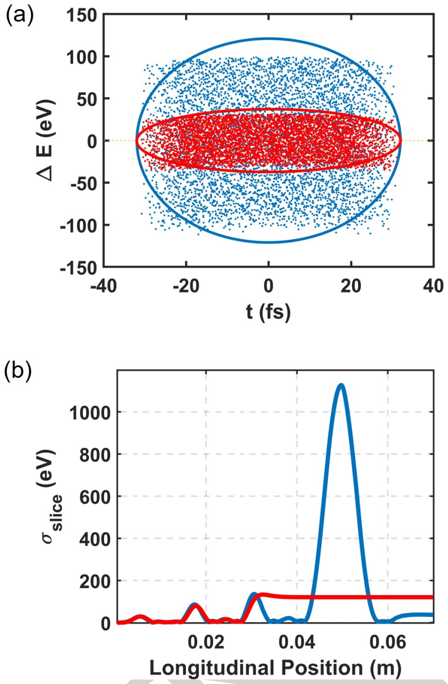

Figure 2: Comparison between the original 2.3-cell gun and the proposed 2.3–2.3 cell structure. (a) Longitudinal phase space at the gun exit. (b) Evolution of slice energy spread along the gun.

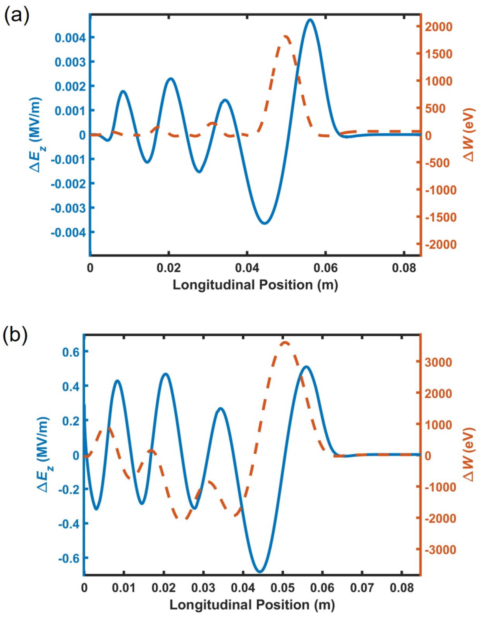

Figure 3: Single-particle tracking results in the proposed structure. (a) Spatial-dimension effect: ΔE_z and ΔW between an on-axis particle and an off-axis particle at $r = 50\ \mu\text{m}$ emitted simultaneously. (b) Temporal-dimension effect: ΔE_z and ΔW between two on-axis particles emitted with a 50 fs time interval.

To explore the compression limit of the 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 simulations show a typical non-monotonic behavior: the slice energy spread first decreases and then rises again as R_E increases. The optimum compensation occurs at $R_E = 1.35$, where the minimum 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 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. 4. Figure 4(a) shows that, compared with the original 2.3-cell gun, the 4.6-cell structure provides substantially better suppression of the 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 slice energy spread even at large spot sizes. Figure 4(b) further shows that the proposed structure preserves a much lower 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 slice energy spread effectively, but also maintains good tolerance to variations in the initial beam parameters.

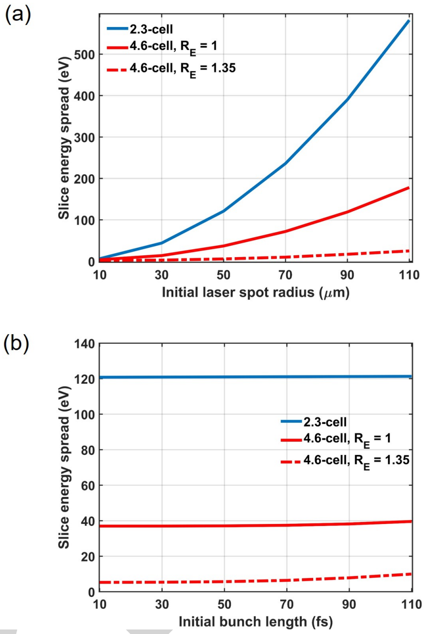

Figure 4: Slice energy spread versus initial beam parameters. (a) Initial laser spot radius. (b) Initial bunch length. Blue: 2.3-cell; red solid: 4.6-cell with $R_E = 1$; red dashed: 4.6-cell with $R_E = 1.35$.

APPLICABILITY UNDER SPACE-CHARGE EFFECTS

To evaluate the applicability of the proposed structure under more realistic conditions, the dependence of the 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 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, which gradually dominate the slice-energy-spread 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 slice energy spread, whereas in the tail region it partially cancels the RF contribution and reduces the 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 photocathode RF gun with a cascaded cavity with a decelerating field is proposed to suppress the slice energy spread of ultrashort electron bunches. The proposed structure reduces the 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 results from the combined action of temporal phase focusing and spatial radial compensation in the cascaded cavity, while preserving the quasi-DC operating characteristics of the original gun. 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 as nonlinear space-charge effects gradually dominate the slice-energy-spread evolution. These results demonstrate an effective compensation scheme for RF-dominated slice-energy-spread growth and a promising route toward low-slice-energy-spread RF guns for ultrashort bunch generation.

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