16th International Particle Accelerator Conference, Taipei, Taiwan JACoW Publishing
ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-WEPS020

PRELIMINARY STUDY OF HIGHER-ORDER MODE BASED SCHEME FOR BUNCH LENGTH COMPRESSION IN SRF ELECTRON GUNS

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Abstract

Higher-Order Modes (HOMs) in superconducting radiofrequency (SRF) cavities are traditionally considered detrimental to efficient operation. They are often associated with beam instabilities and are actively damped. However, these "harmful" HOMs, if used strategically, can be transformed into a tool for providing extra control over the beam, which can introduce new opportunities that are not easily achievable by conventional SRF cavity-based systems. Particularly, we have investigated the feasibility of boosting ballistic bunch compression using HOMs in SRF gun. The proposed idea will be presented with preliminary simulation results. The 185 MHz SRF gun cavity used for the simulation study was modelled using the ACE3P software suite and further modelling of the compression scheme was performed using the GPT code.

INTRODUCTION

Ultrafast electron diffraction (UED) has emerged as a powerful technique for probing structural dynamics in matters and molecules with femtosecond temporal resolution. One of the limitation of existing UED facilities is its limit on the repetition rate due to the use of normal conducting guns. There has been several research to utilize superconducting radio frequency (SRF) guns for UED [1]. In addition, it may be possible to integrate this effort with another effort to introduce additional RF fields in different frequency for improving the beam quality.

In this work, we propose and model a novel scheme that mixes the fundamental and higher-order modes to enhance ballistic bunch compression from SRF guns. By exciting both the fundamental mode (FM) and a higher-frequency mode (HOM) with independently controlled phase, the energy–time correlation (chirp) of the beam can be finely adjusted. The additional degrees of control introduced by the HOM enhances the compression and may partially linearize the longitudinal phase space. This approach is particularly well-suited for developing high-repetition compact UED facility.

We model the scheme using two-modes of RF field and evaluate the performance through particle tracking simulations. The simulation framework comprises of electromagnetic field distributions generated using ACE3P software suite with particle tracking in GPT [2]. RF field maps from ACE3P were imported into GPT to simulate realistic beam–field interactions, including space charge effects as shown in Fig. 1.

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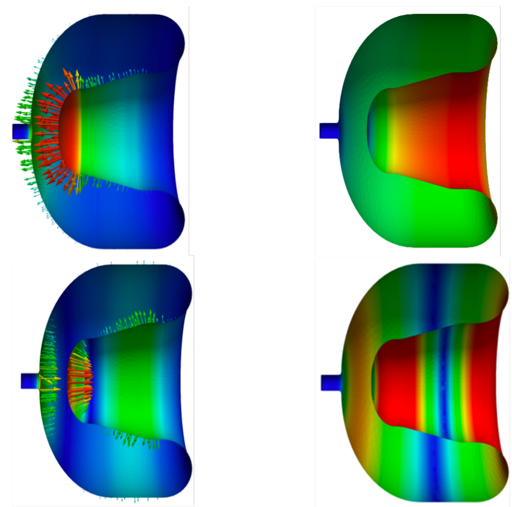

Figure 1: Simulated 3D field pattern in the gun. The top row correspond to fundamental mode, and the bottom row is for higher order mode. The left and right column corresponds to electric and magnetic fields, respectively.

SIMULATION DETAILS

The performance of the proposed hybrid ballistic bunching scheme was assessed through particle tracking simulations. We aimed to evaluate the impact of the HOM field on the bunch's energy and time correlation and longitudinal dynamics. The fundamental and a higher order monopole mode of RF electron gun were superimposed in the same cavity. The HOM was specifically chosen to have a similar accelerating field along the beam axis as that of the fundamental mode.

RF Field Distributions

The RF behavior in the gun was simulated using Omega3P. Omega3P computes the exact modal field distributions and frequencies by solving Maxwell's equations in the actual 3D cavity geometry. The Omega3P field solutions were post-processed using the Acdtool to generate composite field distributions, which were then converted to GDF format to be used as an input for GPT simulations.

Beam Dynamics Simulation

The initial beam condition was set to be similar to the conditions of typical UED facilities [3,4]. The laser radius was set to 100 μm with uniform transverse profile and the temporal distribution was set to a Gaussian profile with 0.1 ps RMS pulse duration. A total charge of 1 pC was modeled with 10k particles.

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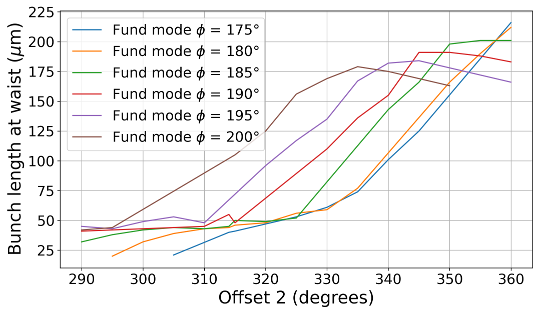

Figure 2: Bunch lengths at the beam waist with different phase combinations.

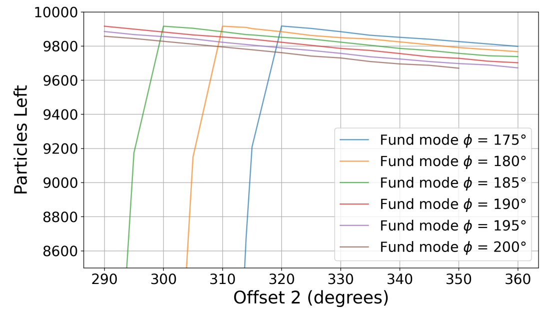

Figure 3: Particles remaining at the end of beamline.

The beam interacts with a superimposed dual-mode RF field inside the gun. The frequency of the fundamental mode is 185.8 MHz, and a higher harmonic mode's frequency is 526.2 MHz. The phase for each mode were scanned to estimate their impact on the beam and find optimized conditions. The FM phase was scanned from 170° to 200°, and the HOM phase was scanned from 290° to 360°.

The physical length of the gun is approximately 30 cm with the accelerating gap of 10 cm. It is followed by an idealized solenoid, with 100 A and 200 turns, placed at 20 cm downstream of the gun exit. While the solenoid is important component that determines the transverse dynamics, particularly the transverse emittance, we focus on the longitudinal dynamics and the solenoid only provides the transverse beam confinement.

Particle distributions were recorded every 10 ps and the longitudinal beam waist was identified from these simulated data.

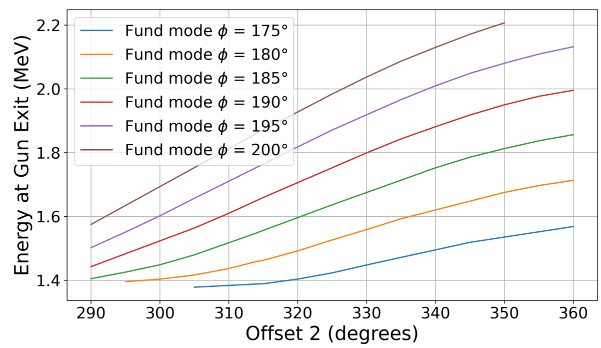

Figure 4: Beam energy at the gun exit.

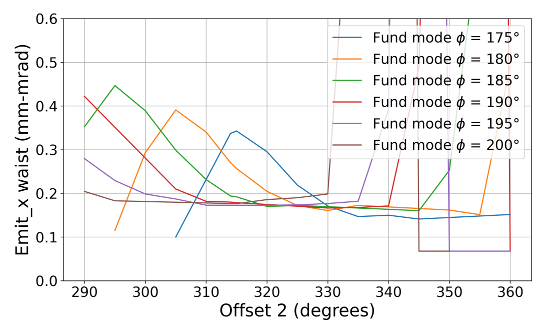

Figure 5: Transverse Emittance at the beam waist.

PHASE DEPENDENCY OF BEAM PROPERTIES

Several beam parameters were monitored during scanning both FM and HOM Phases. While the HOM phase where the bunch length converges depends on the FM phase, the converged bunch lengths were all around 40 μm as shown in Fig. 2. This bunch length is much shorter than what we achieved without HOM field (100-200 μm). The phase combinations that reach below 40 μm are the consequence of the particle loss shown in Fig. 3.

It is worth noting that the zero phase where the emission starts for FM field is 170°. On the other hand the zero phase for HOM field is 315°. So the phase space providing extra compression in Fig. 2 are all generating deceleration of the beam near the cathode. This results in a lower beam energy at the exit of the gun as shown in Fig. 4.

Similar to the bunch length, the transverse emittance also shows converging pattern as seen in Fig. 5. Here the significant growth occurs where the particles loss starts due to the space-charge limited emission.

COMPARISON OF FM AND FM+HOM

Among the range we simulated, we selected the FM phase of 200° and HOM phase of 295° for the comparison. At this phase combination, the bunch length at the waist reaches 40 μm. No particle loss occurs due to the space-charge limited emission, and transverse emittance is around 0.2 μm. The beam energy is little above 1.6 MeV.

Figure 6 and Fig. 7 show the evolution of rms bunch length, longitudinal phase spaces at the gun exit and the waist, and corresponding density profile. Each corresponds to the gun driven by FM field without and with the HOM field, respectively. This comparison provides clear evidence that the HOM enhances bunch compression.

Due to space-charge effect, which produces positive chirp, the chirp can become zero before the bunch is compressed enough when the chirp at the gun exit doesn't exceed some

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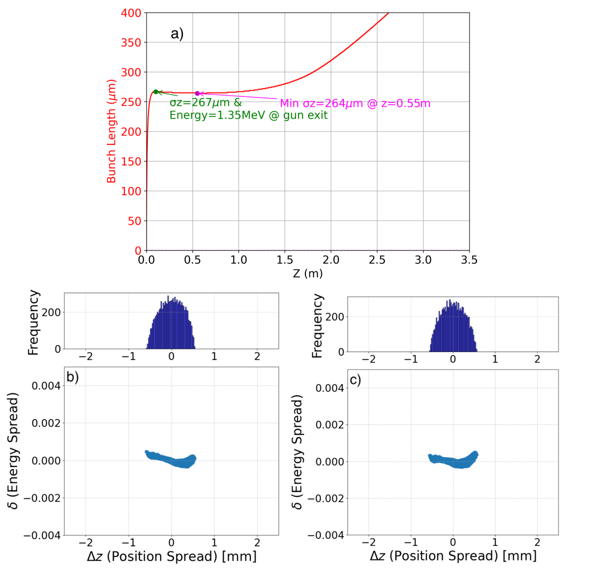

Figure 6: Beam evolution with FM field. (a) Bunch length envlope. (b-c) Longitudinal phase space at the gun exit and longituidnal waist.

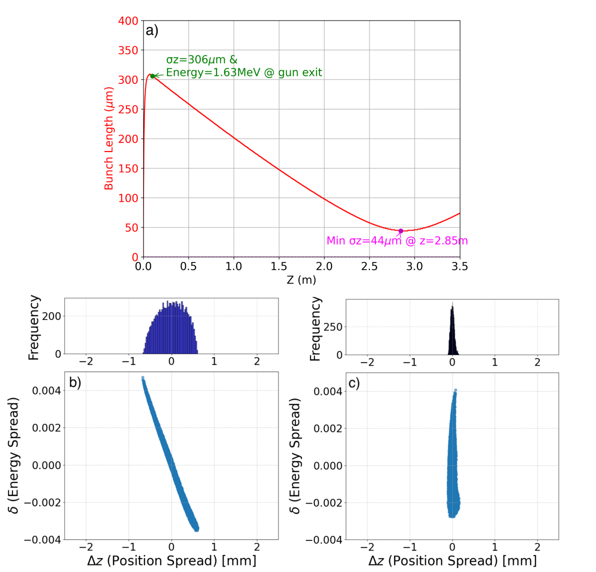

Figure 7: Beam evolution with both FM and HOM fields. (a) Bunch length envelope. (b-c) Longitudinal phase space at the gun exit and longituidnal waist.

critical value. Thus, in the case of Fig. 6, bunch is slightly compressed due to the initial chirp but rapidly reached the waist before it is fully compressed. On the other hand, the HOM field imparts nearly factor of ten higher chirp than the previous case. Thus, the critical compression is accomplished before the space-charge turns the chirp zero.

It is important to note that the increase of FM field strength does not improve this space-charge related behavior. Figure 8 shows the result with doubled FM field strength. While the bunch length at the gun exit is reduced due to fast acceleration near the cathode, its bunch length evolution resembles that in Fig. 6. Although further analysis is required to con-

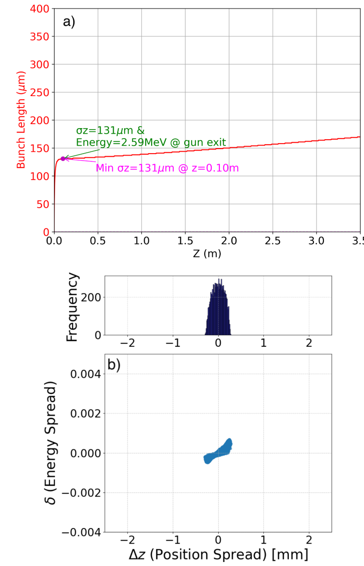

Figure 8: Beam evolution with FM field whose strength is doubled. (a) Bunch length envelope. (b-c) Longitudinal phase space at the gun exit and longitudinal waist.

clude, it seems that the compression enhancement by HOM cannot be replicated by adjusting FM field's strength and phase.

CONCLUSION

We simulated the beam dynamics under various phases of FM and HOM fields. When the HOM fields was initially in a decelerating phase, it provided additional compression to the bunch. A direct comparison between FM-only and FM+HOM configurations clearly demonstrated that the HOM field significantly enhances bunch compression. Further investigation is needed to correlate this result with the behaviour of the transverse emittance, which is essential for realizing HOM-assisted SRF gun-based UED.

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