# FIRST-PRINCIPLE BEAM-DYNAMICS SIMULATIONS OF ALPHA MAGNETS FOR BUNCH COMPRESSION OF BRIGHT BEAMS *

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*Abstract*

Producing bright electron beams is crucial for coherent light sources, where increasing the peak current is typically accomplished through bunch compression in magnetic chicanes. Alpha magnets, with their unique phase-space manipulation capabilities, have emerged as an attractive choice for compressing sub-10 MeV electron beams generated by radio frequency photoinjectors. This paper presents detailed numerical modeling of the beam dynamics of high-charge, bright bunches undergoing compression within an alpha magnet. The model incorporates space-charge effects and coherent synchrotron radiation, providing a comprehensive understanding of the complex interactions and behaviors of the electron beams during the compression process.

## INTRODUCTION

Coherent light sources require bright electron beams with high peak currents. To increase the bunch peak current, longitudinal bunch compression in magnetic chicanes is commonly employed. This process necessitates an energy chirp in the electron bunch—a correlation between the particles' longitudinal positions and their energies—which is typically introduced by RF accelerating structures. Consequently, using chicanes for compression often requires a relatively large system and is more suitable for high energies (> 10 MeV). For compressing sub-10-MeV beams, a shorter and more compact system is desirable. In this context, alpha magnets combined with RF guns present an attractive and effective compression scheme for compact injector systems. Similarly, this class of magnet has been extensively used in conjunction with thermionic RF guns to generate bunch trains for injection into storage ring complexes. [1].

An alpha magnet can be assimilated to a half-quadrupole magnet. In the ideal alpha magnet considered in this paper, a particle injected at an angle of 40.71° to the normal of the magnet entrance exits at the same angle, regardless of its energy. The particle's trajectory within the magnet forms a path resembling the letter alpha ($\alpha$). Alpha magnets were originally used as achromatic magnetic mirrors for ion beams [2]. Detailed particle dynamics in the alpha magnet and its characteristics are described in [3]. Due to their unique phase-space manipulation capabilities, alpha magnets have garnered significant interest as bunch compression schemes for low-energy electron beams, particularly in applications like coherent light generation; see, e.g., [4–10]. The particle's path length inside the alpha magnet varies depending on its energy such that high energy electrons follow a longer path than that of the lower energy electrons. Therefore, an energy chirped beam will be compressed after passing through the alpha magnet similarly to the magnetic chicane, but with a positive chirp in this case (i.e. high-energy head and low-energy tail). The chirp can be provided by the RF photoinjector, and hence the compression can be performed at a low energy right after the gun without the need for an RF accelerating structure.

At low energies, space charge forces are particularly strong, especially for higher bunch charges. Additionally, the bending of electron trajectories through the alpha magnet causes the emission of synchrotron radiation, which becomes coherent for short bunch lengths. Therefore, detailed numerical modeling of the beam dynamics for high-charge, bright bunches undergoing compression in an alpha magnet—including space charge effects and coherent synchrotron radiation (CSR)—is essential. Studies on beam dynamics and space charge simulations are available in Refs. [11–15].

In this paper, we present beam dynamics simulations of alpha magnet bunch compression using the first-principles, large-scale CSR model, the LW3D code, which naturally incorporates both space charge and CSR effects. The aim is to investigate the impact of CSR on beam brightness.

## SIMULATION METHOD

The basic approach to CSR involves computing the 3D electromagnetic radiation fields directly from the Liénard-Wiechert potentials. The LW3D code, developed by Ryne [16], is the only first-principles implementation for 3D CSR computation. It is a large-scale parallel program that calculates CSR fields on a 3D grid at each time step. These fields are then applied to the particles by interpolating them at each particle's position over time, a method referred to as the self-consistent mode of LW3D.

An important feature of the LW3D algorithm is its ability to consider arbitrary external electric and magnetic fields while most other available CSR codes are limited to dipole magnets. This feature is essential for the alpha-magnet simulation as we can easily include its fields in the code or import the field map from a file.

While CSR effects can be mitigated through shielding [17], the current implementation of the LW3D code does

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not account for shielding and assumes free-space propagation. Additionally, in typical alpha magnet bunch compression applications, energy slits are often inserted within the magnet to filter out particles outside a specific energy range, thereby improving beam quality. However, our simulations do not include energy slits. Despite these exclusions, the model incorporates both space charge effects and CSR, offering a comprehensive understanding of the complex interactions and behaviors of electron beams during the alpha magnet compression process.

## ALPHA MAGNET SIMULATIONS

The non-vanishing magnetic-field components associated with an ideal alpha magnet are

$$B_y = gz, \text{ and } B_z = gy. \tag{1}$$

Here $g$ is the magnetic-field gradient. We rotate the alpha magnet axis by 40.71° in our model and the beam propagate along the direction $\hat{z}$. This angle corresponds to the injection angle that produces a self-similar trajectory for different injection energies, with the exit point and angle similar to those at injection. For our simulation, we maintained the gradient constant at $g = 10\,\mathrm{T/m}$. The initial electron beam has an energy chirp $h = (\partial z)/(\partial\delta)$ (with $\delta$ being the relative momentum spread) that is tuned to achieve maximum compression by ensuring that $h^{-1} \simeq -R_{56}$ the longitudinal dispersion of the alpha magnet. The other beam parameters are listed in Table 1.

Table 1: Electron Beam Parameters in the Alpha Magnet Simulations

| **Parameter** | **Value** | **Unit** |
|---|---|---|
| Bunch charge | 1 | nC |
| Energy | 5 | MeV |
| Bunch length $\sigma_z$ | 5 | mm |
| Absolute uncorrelated $\Delta\gamma$ | 0.04 | |
| Current | 25 | A |
| Normalized emittance $\varepsilon_x$ | 1 | µm |

The reference particle trajectory through the alpha magnet appears in Fig. 1 (a) as simulated with the LW3D without including CSR interactions. Figure. 1 (b) shows the evolution of the bunch length which decreases from its initial value of 5 mm to 368 µm in this example.

We turn on CSR interactions in the LW3D code and compare the results with that when CSR interactions are off. The longitudinal phase-space (LPS) with CSR-on in Fig. 2 (c) is distorted compared to that with CSR-off in Fig. 2 (a). The current was enhanced from 25 A to 560 A without CSR interactions in Fig. 2 (b), while the CSR effect results in a significant decrease of the final peak current to 302 A in Fig. 2 (d).

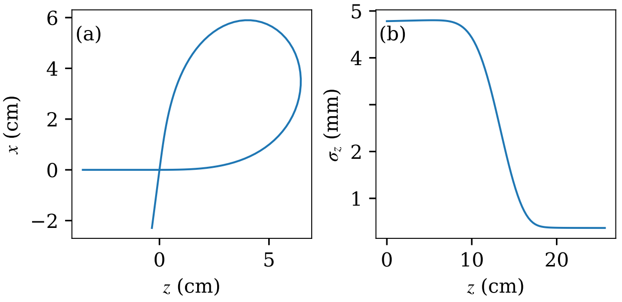

Figure 1: LW3D simulation of the alpha magnet bunch compression without CSR interactions showing the trajectory of the reference particle (a), and the evolution of the bunch length (decreasing) (b).

Since the alpha magnet couples the longitudinal and transverse planes, we expect the impact of CSR on the longitudinal phase-space (LPS) to also manifest in the transverse phase-space (TPS). This is illustrated in Fig.3(b), where TPS distortion is evident when CSR interactions are enabled, compared to the undistorted TPS shown in (a) when CSR interactions are disabled.

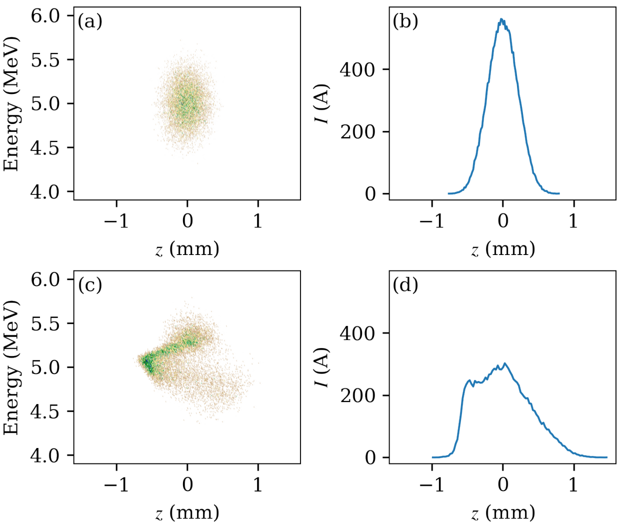

Figure 2: LW3D simulation results of the alpha magnet bunch compression. When CSR interactions are off: (a) the LPS and (b) the current. When CSR interactions are on: (c) the LPS and (d) the current.

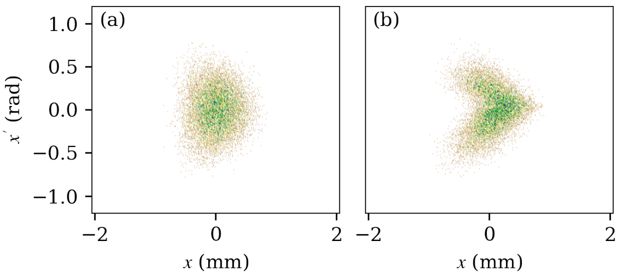

Figure 3: Transverse phase-space resulted from the LW3D simulations of the alpha magnet bunch compression: (a) when CSR interactions are off, and (b) when CSR interactions are on.

Finally, we examine the impact of the CSR wakefield on the beam within the alpha magnet, as observed in our simulations. Figure 4 illustrates both the longitudinal and transverse wakefields. Although these wakefields resemble those produced by a steady-state dipole field, they are notably weaker.

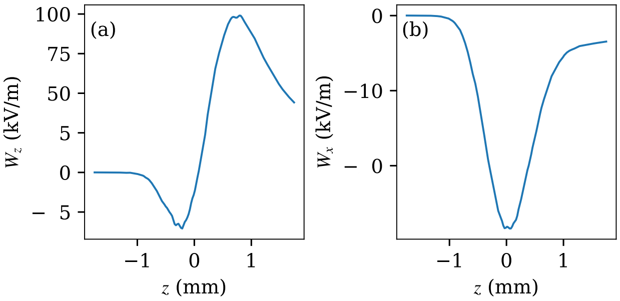

Figure 4: CSR longitudinal wakefield (a) and transverse wakefield (b) of the alpha magnet bunch compression simulated by the LW3D code.

## CONCLUSION

We performed first-principle beam dynamics and CSR simulations for bunch compression in the alpha magnet. Our results demonstrated a peak current enhancement by at least an order of magnitude, with the bunch length compressed by a factor of approximately 12. However, CSR interactions led to distortions in both the longitudinal and transverse phase-spaces and a reduction in the final peak current. The developed model will be utilized to benchmark simulations of high-charge bunch compression for THz generation using an alpha magnet downstream of an RF photoinjector. Additionally, it will serve as a high-fidelity model for thermionic injectors used in the Advanced Photon Source injection complex.

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