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Author
Lee, Amy

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Amy Lee[1]

[1] *Undergraduate in Electrical Engineering, UCLA*

Abstract: A Laguerre-Gaussian mode laser better suppresses microbunching instability in electron beams than standard Gaussian lasers. A shorter-wavelength laser enables refined microbunching suppression, improving energy modulation and enhancing free-electron laser performance.

INTRODUCTION

Free-electron lasers (FELs) are critical tools in science, providing extremely bright and precise light for applications like imaging and spectroscopy. However, FEL performance can be limited by microbunching instability (MBI), where small disturbances in the electron beam grow and degrade beam quality. To fix this, FEL systems use a laser heater, which spreads out the energy in the electron beam in a controlled way to dampen these disturbances.

Current laser heaters often use infrared (IR) lasers with a Gaussian beam shape. While effective, these configurations can produce uneven energy distributions, such as double-horn profiles, which are less effective at suppressing MBI. Recent advancements suggest that Laguerre-Gaussian (LG01) mode lasers with donut-shaped intensity profiles create smoother energy distributions, thereby improving MBI suppression. This study explores the optimization of the laser's wavelength to further enhance FEL performance.

The suppression factor quantifies the laser heater's ability to damp microbunching instabilities (MBI), which degrade the electron beam quality and, consequently, the FEL performance. The suppression factor decreases exponentially with increasing wavenumber $k = 2\pi / \lambda$. This makes shorter wavelengths (higher k) more effective at reducing MBI. By calculating S(k), we ensure the chosen wavelength effectively suppresses instabilities while minimizing technical challenges.

Photon energy determines the strength of the interaction between the laser and the electron beam, which drives energy modulation. Higher photon energy leads to stronger coupling with the electron beam, enabling uniform energy distribution and better suppression of high-frequency instabilities. The population ratio determines the feasibility of achieving population inversion in the laser gain medium, which is necessary for stable laser operation. Calculating population ratio ensures the chosen wavelength aligns with the physical capabilities of available laser systems, balancing suppression and operational feasibility. Therefore, by analyzing these parameters—suppression factor, photon energy, and population ratio—the selected wavelength can optimize FEL performance while minimizing system complexity.

METHODS

The suppression factor $S(k) = e^{-k^2 R_{56}^2 A^2}$ where $k = 2\pi / \lambda$ is the wavenumber and inversely proportional to the laser wavelength, R_{56} is the bunch compressor parameter, A is the mode matching ratio. Using chosen wavelengths of 200 nm, 400 nm, 800 nm, and 1000 nm, the respective k values of $6.28 * 10^6$, $7.85 * 10^6$, $1.57 * 10^7$, $3.14 * 10^7\ m^{-1}$ were calculated. Using Tang et al.'s paper for the values A = $\sigma_r/\sigma_x = 325/50 = 6.5$ and Liebster et al.'s results for R_{56} = 45 mm, S(k) was computed for each wavelength.

Additionally, photon energy was calculated based on the equation $E = hc/\lambda$, where h is Planck's constant and c is the speed of light. Finally, the population ratio was derived using the Boltzmann relation: $\frac{N_2}{N_1} = \frac{g_2}{g_1} e^{-(E_2 - E_1)/k_B T}$, where k_B is the Boltzmann constant, T is room temperature (300 K), $E_2 - E_1$ corresponds to the photon energy and the gain g is assumed to be 1. The calculated values are summarized in Table 1.

Wavelength (nm)	Suppression Factor	Photon Energy (eV)	Population Ratio
200	0	6.20	0
400	0	3.10	7.39e-53
800	0	1.55	8.6e-27
1000	0	1.24	1.4e-21

Table 1. Summary of suppression factors, photon energies, and population ratios for Laguerre-Gaussian mode laser heater at different wavelengths.

RESULTS AND INTERPRETATION

The results of this study indicate that the suppression factor S(k) approaches zero for all tested wavelengths, owing to the large exponential term in the equation. This demonstrates the high effectiveness of the Laguerre-Gaussian laser heater in suppressing microbunching instabilities (MBI) across all wavelengths analyzed. Shorter wavelengths produced larger wavenumbers k, enhancing the suppression effect due to their stronger exponential decay.

Photon energy, calculated as $E = hc/\lambda$, was shown to decrease significantly with increasing wavelength. For example, the photon energy at 200 nm was 6.20 eV, compared to 1.24 eV at 1000 nm. Higher photon energy strengthens the interaction between the laser and the electron beam, allowing for more uniform energy modulation and improved suppression of high-frequency MBI components. However, shorter wavelengths also result in negligible population ratios, making population inversion nearly impossible under thermal equilibrium at room temperature. At all wavelengths, the population ratio is extremely small, reflecting the need for advanced gain media or external energy sources to achieve population inversion. This trade-off highlights the challenges of achieving operational feasibility at shorter wavelengths.

To achieve these improvements, technologies such as spiral phase plates are used to create Laguerre-Gaussian (LG01) profiles, which further enhance suppression by creating a more uniform energy distribution. Beamlet arrays, consisting of grids of smaller beams, offer additional control over the energy spread and reduce sensitivity to alignment errors, making them an attractive solution for future FEL systems.

CONCLUSIONS

This study demonstrates that shorter wavelengths in Laguerre-Gaussian mode lasers enhance microbunching instability suppression in FELs due to higher photon energies and stronger interactions with the electron beam. However, the implementation of shorter wavelengths requires addressing challenges related to population inversion and gain medium design. Future work should explore laser materials and system designs to overcome these limitations.

REFERENCES

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