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Exploring Wavelength for Enhanced Microbunching Instability Suppression in Free-Electron Lasers

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Abstract: Microbunching instability greatly impacts free-electron laser performance by degrading the quality of the electron beam, directly affecting the laser's output. This study uses laser wavelength adjustments to maximize MBI suppression while minimizing beamline complexity.

INTRODUCTION

Free-electron lasers (FELs) are used by physicists, chemists, and biologists to analyze matter at the atomic and molecular level. With FELs, we can understand breakthroughs in fundamental processes and gain insights into the properties of advanced materials. However, for FELs to function most efficiently, the electron beam it uses must maintain high coherence.

Microbunching instability (MBI) occurs in particle accelerators when small density variations—known as microbunches—in the electron beam grow exponentially, leading to increased energy spread and reduced beam quality. MBI can result from density or energy variations within the beam, or from interactions with external electromagnetic fields that convert energy modulations into density modulations. The degradation of the electron beam's coherence due to MBI results in heightened noise in the FEL output, reducing efficiency and power. Tang, et al. explore using a Laguerre-Gaussian (LG) mode laser heater to mitigate MBI, as LG mode lasers have unique intensity and phase distribution as opposed to conventional Guassian mode lasers. The LG mode donut-shaped intensity profiles with helical waveforms and orbital angular momentum provides spatial control over energy modulation introduced to the electron beam as it propagates, giving LG mode lasers the ability to disrupt the growth of density modulations. Tang, et al. use this to create a theoretical model that simulates the interaction between the LG laser and the electron beam.

The enhanced stability and efficiency of FELs can improve accuracy in experiments, which can lead to advancements in areas like structural biology and materials science. In the context of photonics, this research may reshape our understanding of light-matter interactions. LG mode lasers carry orbital angular momentum, which can offer new ways to manipulate light, and this can directly impact fields like telecommunications and quantum information technologies, where the ability to control light's spatial and angular properties is critical. This study will explore how varying wavelength—from ultraviolet to infrared ranges—will impact MBI suppression efficiency by analyzing how this changes energy deposition and the associated microbunching suppression.

METHODS

The following equation describes the energy density distribution of a Laguerre-Gaussian mode laser [4][5]:

$$I(r,\phi,z) = I_0\left(\frac{r\sqrt{2}}{w(z)}\right)^{2p} L_p^{|l|}\left(\frac{2r^2}{w^2(z)}\right)^2 exp\left(-\frac{2r^2}{w^2(z)}\right) cos^2(l\phi)\frac{w_0^2}{w^2(z)} \quad (1)$$

Where:

- I_0 is the peak intensity at the beam center
- r is the radial distance from the beam axis
- $w(z) = w_0\sqrt{1 + (\frac{z}{z_R})^2}$ is the beam waist at position z
- w_0 is the beam waist at the focus
- $z_R = \frac{\pi w_0^2}{\lambda}$ is the Rayleigh range
- p and l are the radial and azimuthal mode indices
- $L_p^{|l|}$ is the associated Laguerre polynomial
- $k = \frac{2\pi}{\lambda}$ is the wave number
- λ is the wavelength

For donut-shaped beams, the parameters p and l are 0 and 1, respectively. The energy density equation from (1) then becomes

$$I(r,z) = I_0 \frac{2r^2}{w^2(z)} exp(-\frac{2r^2}{w^2(z)}) cos^2(\phi) \quad (3)$$

To analyze the effectiveness of microbunching suppression, the energy spread for the various cases can be compared. The energy spread ΔE equation for laser power P_L is given by [5]

$$\Delta E \propto \sqrt{P_L \lambda} \quad (4)$$

This relation shows that to maintain the same level of microbunching suppression as wavelength changes, the laser power must be adjusted accordingly.

Using these equations and varying wavelength, assuming constant beam waist $w_0 = 100\mu m$ and laser power $P = 1\ W$ we obtain the following energy densities:

Table 1. Parameters and Calculations with Varying Wavelengths

	$\lambda(nm)$	$z_R(mm)$	$w(z_R)(\mu m)$	$I(0,0)\ (W/cm^2)$	$I(0,z_R)\ (W/cm^2)$
UV-C	254	123.7	141.4	6.37×10^4	3.18×10^4
UV-A	365	86.1	141.4	6.37×10^4	3.18×10^4
Visible (Green)	532	59.1	141.4	6.37×10^4	3.18×10^4
Near-IR	1064	29.5	141.4	6.37×10^4	3.18×10^4
Fiber Optics Communication	1550	20.3	141.4	6.37×10^4	3.18×10^4

Using Matlab, we plot wavelength against other variables to better visualize how varying wavelengths affect laser parameters:

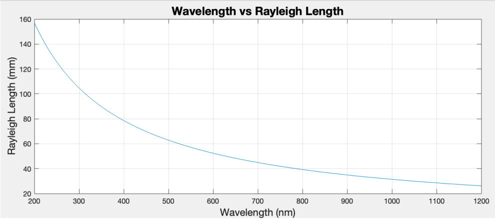

Fig. 1 MATLAB plots of Wavelength vs. Rayleigh Length [6]

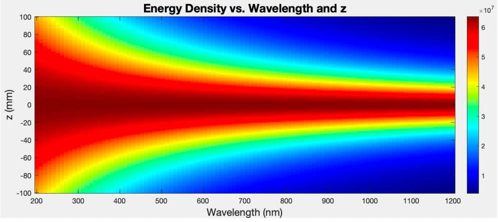

Fig. 2 MATLAB plots of Wavelength vs. Energy Density [6]

RESULTS AND INTERPRETATION

From Table 1 and Figure 1, we see that Rayleigh range z_R has a strong inverse relationship with wavelength. This means that beams with longer wavelengths will diverge from the waist more quickly, limiting how far the beam can remain tightly focused and directly impacting the applications that require long-distance propagation. Figure 2 helps us understand how wavelength affects beam propagation characteristics. In particular, we see that the rate at which energy density decreases with z varies with different wavelengths, and shorter wavelengths maintain high energy densities over longer distances.

Table 1 shows that the beam waist at the Rayleigh length $w(z_R)$ remains constant, and only depends on the initial beam waist. This indicates that the beam's divergence behavior is consistent across different wavelengths, and the primary difference is the rate at which the divergence occurs. In the context of laser heaters for FELs, a constant beam waist and predictable divergence behavior is beneficial for maintaining uniform energy spread in the electron beam. Figure 2 shows that the divergence pattern of energy density is symmetric on both sides of the beam waist, forming a characteristic hourglass shape. While the peak energy density distribution $I(0,0)$ is the same for all wavelengths from the ultraviolet (UV) to the infrared (IR) range, the spatial distribution varies due to different Rayleigh ranges. This is due to the fact that total energy in the beam must remain constant, so the energy spreads over a large area and reduces local energy density as the beam expands. This means that UV wavelengths can be used for high-intensity interaction lengths, whereas IR wavelengths are more suitable for large area processing.

CONCLUSIONS

In conclusion, varying wavelengths for the Laguerre-Gaussian mode laser varies the spatial energy density distribution of electron beams: shorter wavelengths propagate beams farther with greater resolution, and longer wavelengths cause beams to diverge more rapidly. The energy density is highest and most concentrated at the beam waist for all wavelengths, with symmetric divergence on all sides. This symmetry matches ideal Gaussian beam properties, including a flat wavefront at the waist and consistent power distribution. Shorter wavelengths focus to smaller spot sizes, resulting in concentrated high-energy density regions near the beam waist. This characteristic, along with the wavelength-dependent divergence patterns, has significant implications for beam shaping and application-specific wavelength selection.

Physical experiments across the UV to IR range can validate these theoretical calculations, comparing actual beam propagation characteristics with predicted values. The findings can have a significant effect on optical system design, laser setup optimization, and beam behavior in photonics applications. Specific wavelengths can be selected for specialized applications such as microbunching suppression in free-electron lasers (FELs) or laser mode propagation, highlighting the wide-range impact of these insights.

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