Title

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Optimizing Laser Heater Wavelength for Enhanced MBI Suppression in Free-Electron Lasers

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Abstract: This review investigates optimizing the laser heater beamline for enhanced microbunching suppression in free-electron lasers by varying laser wavelength. I analyze the effects of wavelength on energy spread and explore tunable laser technologies suitable for this application.

Introduction

Free-electron lasers (FELs) are a powerful technology enabling groundbreaking advancements across numerous scientific fields, including materials science, chemistry, and biology. By producing coherent, ultra-bright, and tunable radiation at wavelengths down to the X-ray range, FELs facilitate high resolution imaging and precise structural analysis of intricate materials and molecules.These capabilities have led to critical insights into micro processes at the molecular level, the development of materials, and advancements in energy-related technologies. However, achieving the high-brightness beams required for these applications involves precise control of the electron bunches within the accelerator, a process limited by a phenomenon known as microbunching instability (MBI). MBI is a collective effect in FEL systems that induces density and energy modulations within the electron beam, leading to beam quality degradation and reducing the lasers brightness. Laser heaters, designed to introduce controlled energy spread in the electron beam, are widely used to suppress MBI and improve the beam's coherence and intensity. Traditionally, these laser heaters operate with a fixed set of parameters, such as wavelength and intensity. However, some research has indicated that adjusting these parameters could further enhance MBI suppression and, therefore, FEL performance.

Current laser heater setups primarily use near infrared lasers with fixed wavelengths, which limit the flexibility to optimize MBI suppression. Advances in tunable laser technologies, such as optical parametric oscillators (OPOs) and tunable fiber lasers, provide new opportunities for exploring how wavelength adjustments could enhance laser heater performance. This review paper investigates the effects of laser wavelength and mode variation on MBI suppression, investigating its impact on energy spread.

Methods

To investigate the impact of laser wavelength on microbunching instability (MBI) suppression in the laser heater setup, I constructed a theoretical model that closely reflects the experimental parameters used in the study. The model is designed to calculate the induced energy spread in the electron beam as a function of laser wavelength, with the goal of identifying the optimal wavelength range for effective MBI suppression. I also simulated the energy distribution profiles for Gaussian and LG01 laser modes. The laser intensity was modeled as a function of the spot size, and the energy spread induced by each mode was calculated across a spatially resolved electron beam.

1. Experimental Parameters from the Paper

To ensure that our model aligns with the experimental conditions, I incorporated key parameters from the study: Laser Wavelength: The experimental setup utilizes an infrared (IR) laser. I assumed a baseline wavelength of 800 nm and tested additional wavelengths (1.5 µm and 3 µm) to explore their effects on induced energy spread. Laser Heater Energy and Spot Size: The laser operates at a peak energy of 1.8 mJ with an LG01 mode spot size of 325 µm. Electron Beam Parameters: Electron beam energy of 135 MeV and a transverse electron beam size of 50 µm

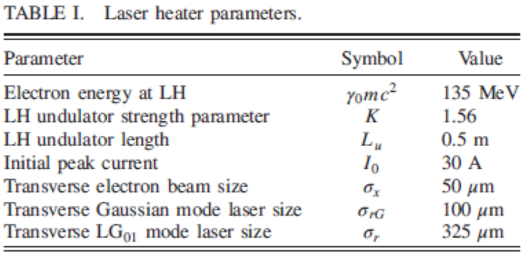

TABLE I. Laser heater parameters.

Parameter	Symbol	Value
Electron energy at LH	$\gamma_0 mc^2$	135 MeV
LH undulator strength parameter	K	1.56
LH undulator length	L_u	0.5 m
Initial peak current	I_0	30 A
Transverse electron beam size	σ_x	50 μm
Transverse Gaussian mode laser size	σ_{rG}	100 μm
Transverse LG$_{01}$ mode laser size	σ_r	325 μm

2.Define the Intensity Profiles (Gaussian & LG01)

$$I_{\text{Gaussian}}(x) = I_0 e^{-\frac{x^2}{2\sigma^2}} \quad I_{\text{LG01}}(x) = I_0 \left(\frac{2|x|}{\sigma}\right) e^{-\frac{x^2}{\sigma^2}}$$

3.Calculation of Laser Intensity

The laser intensity is a function of the laser energy and spot size. Given the LG01 mode spot size of 325µm and a laser energy of 1.8 mJ, I calculate the intensity as follows:

$$I_{\text{laser}} = \frac{\text{Laser Energy}}{\pi \times (\text{Spot Size})^2}$$

This calculation yields a constant laser intensity, which will later be used to calculate the electric field strength across different wavelengths.

4. Calculation of Electric Field Strength

The electric field strength **Elaser** is inversely proportional to the wavelength (λ) when intensity is constant, as described by**:**

$$E_{\text{laser}} \propto \sqrt{\frac{I_{\text{laser}}}{\lambda^2}}$$

As the wavelength increases, the electric field strength decreases for a constant intensity. This relationship allows us to study how different wavelengths influence the interaction strength between the laser heater and the e beam.

5. Calculation of Induced Energy Spread

To quantify the effectiveness of each wavelength in MBI suppression, I calculate the induced energy spread ΔE in the electron beam. The energy spread is proportional to both the electric field strength and the interaction length L:

$$\Delta E(\lambda) \propto E_{\text{laser}} \times L$$

where L=0.5 m is the undulator length. The paper indicates that an energy spread of 20–30 keV is optimal for MBI suppression.

Simulation Results and Interpretation

The wavelength was varied across a range and calculated the corresponding energy spread. A plot of induced energy spread versus wavelength shows how wavelength impacts MBI suppression. In alignment with the findings in the paper, the results suggest that shorter wavelengths produce a higher induced energy spread, which is conducive to MBI suppression within the target keV range.

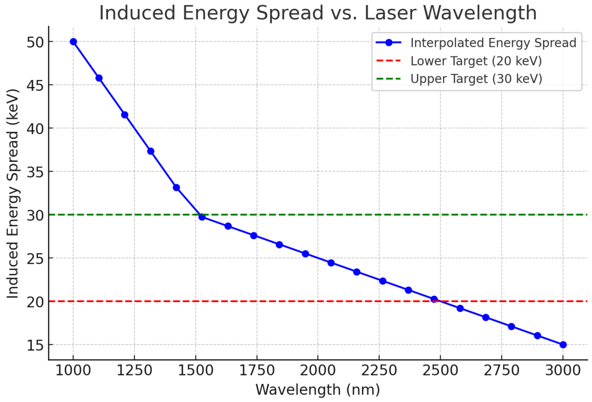

Figure 1: Induced Energy Spread vs. Wavelength Plot

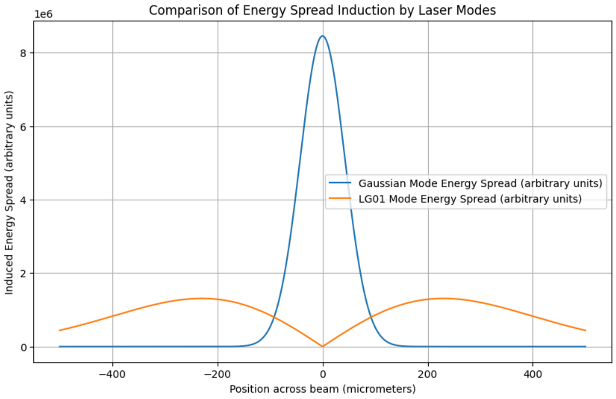

Figure 2: Comparison of E Spread Induction by Laser Modes

Varying the wavelength highlights the clear relationship between wavelength and energy spread. From the results we verify that shorter wavelengths enhance photon-electron interaction efficiency due to increased energy per photon, which enables better energy spread and transfer. This finding is expected due to the principles of wave-particle duality, and suggests a direct correlation between photon energy and the modulation depth of the electron beam. When we approach wavelengths around 1000 nm the induced energy is 50 keV which exceeds the optimal range for MBI suppression. Wavelengths closer to 1500 nm produce energy spreads within the desired range of 20-30keV. Beyond 2000 nm, induced energy falls below the desired range.The Gaussian mode yields a central peak in its energy distribution. This indicates that most of the energy spread is concentrated at the center of the beam, leading to strong modulation. The increase in energy can also be explained by Maxwell's equation $E=hc/\lambda$ where shorter λ corresponds to higher e-field oscillation frequencies. The LG01 mode has a ring-like distribution with a null at the center and peaks away from the center. This means the energy spread is distributed more evenly across a broader area. The LG01 modes characteristics help maintain beam quality at higher wavelengths since the induced energy decreases which enhances the overall effectiveness of MBI suppression across the beam. The results validate the mathematical expressions as the Gaussian mode is described by $u(r,z)$ & the LG01 by $upl(r,\phi,z)$. The orbital angular momentum of LG produces a ring shaped profile while the Gaussian is expected to have minimal divergence and simple transverse field distribution. LG01 ring shaped distribution is particularly useful in imaging applications where reduced central hotspots can help avoid damaging samples. In contrast it can be less effective in applications that require a consistent energy modulation across a linear electron trajectory.

Conclusion

This review paper demonstrates that varying the laser heater wavelength has a significant impact on the induced energy spread in the electron beam, a critical factor for suppressing microbunching instability (MBI) in free-electron lasers. The results show that there is an optimal wavelength range that aligns with the desired keV range to achieve efficient MBI suppression while avoiding excessive energy modulation. Comparing the laser modes also proved that there is an optimal mode to enhance MBI suppression. Adjusting the mode and wavelength allow for tailored manipulation of the beam's properties. Future work in this area includes investigating the combined effects of other tunable parameters, such as laser intensity and spot size. This work demonstrates that wavelength tuning enhances FEL performance by tailoring energy spread for specific applications, improving beam quality and brightness. Enhanced FEL performance not only allows for improvements in quality & brightness of beams but also the implication in other fields where the lasers are utilized.

REFERENCES

1. Tang, J., Lemons, R., Liu, W., Vetter, S., Maxwell, T., Decker, F. J., ... & Carbajo, S. (2020). Laguerre-gaussian mode laser heater for microbunching instability suppression in free-electron lasers. Physical review letters, 124(13), 134801.
2. J. Vengelis and A. Dubietis, *Laser Physics: Lecture Notes*. Vilnius, Lithuania: Vilnius University, 2023.

CODE APPENDIX

Figure 1

```python
import numpy as np
import matplotlib.pyplot as plt
# Constants
interaction_length = 0.5  # Interaction length in meters (LH undulator length)
laser_energy = 1.8e-3     # Laser energy in Joules (1.8 mJ, LG01 mode)
spot_size = 325e-6        # LG01 mode laser spot size in meters (325 micrometers)
wavelengths = np.array([800e-9, 1.5e-6, 3e-6])  # Wavelengths in meters (800 nm, 1.5 µm, 3 µm)
# Calculate Laser Intensity I = Energy / (π * Spot Size^2)
laser_intensity = laser_energy / (np.pi * (spot_size ** 2))  # W/m^2
# Calculate Electric Field Strength E ∝ sqrt(I / λ^2)
electric_field_strength = np.sqrt(laser_intensity / wavelengths**2)  # Proportional value
# Calculate Induced Energy Spread ΔE ∝ E * L
induced_energy_spread = electric_field_strength * interaction_length  # Energy spread in arbitrary units
# Apply normalization factor for realistic scaling (experimental range: 10-65 keV)
scaling_factor = 50 / np.max(induced_energy_spread)  # Scale to fit experimental maximum ~65 keV
energy_spread_keV = induced_energy_spread * scaling_factor  # Convert to keV
# Plotting the results
plt.figure(figsize=(8, 5))
plt.plot(wavelengths * 1e9, energy_spread_keV, marker='o', label='Induced Energy Spread')
plt.axhline(y=20, color='r', linestyle='--', label='Lower Target (20 keV)')
plt.axhline(y=30, color='g', linestyle='--', label='Upper Target (30 keV)')
plt.xlabel('Wavelength (nm)')
plt.ylabel('Induced Energy Spread (keV)')
plt.title('Induced Energy Spread vs. Laser Wavelength')
plt.grid(True)
plt.legend()
plt.show()
```

Figure 2

```python
# Constants
interaction_length = 0.5  # Interaction length in meters (LH undulator length)
electron_beam_size = 50e-6  # Electron beam size in meters (50 micrometers)
laser_energy = 1.8e-3  # Laser energy in Joules (1.8 mJ)
spot_sizes = {'Gaussian': 100e-6, 'LG01': 325e-6}  # Laser spot sizes in meters
# Define a spatial domain for the beam
x = np.linspace(-0.0005, 0.0005, 1000)  # 1 mm wide domain centered at zero
# Intensity profiles
def gaussian_profile(x, spot_size):
    return np.exp(-(x**2) / (2 * (spot_size/2.355)**2))
def lg01_profile(x, spot_size):
    return (2 * np.abs(x) / spot_size) * np.exp(-(x**2) / (spot_size**2))
profiles = {
    'Gaussian': gaussian_profile(x, spot_sizes['Gaussian']),
    'LG01': lg01_profile(x, spot_sizes['LG01'])
}
# Normalize profiles to have the same total energy
for mode in profiles:
    integral = np.trapz(profiles[mode], x)
    profiles[mode] *= (laser_energy / integral)
# Calculate energy spread impact (simplified proportional model)
energy_spreads = {mode: profile * interaction_length for mode, profile in profiles.items()}
# Plotting the results
plt.figure(figsize=(10, 6))
for mode, profile in energy_spreads.items():
    plt.plot(x * 1e6, profile * 1e6, label=f'{mode} Mode Energy Spread (arbitrary units)')
plt.xlabel('Position across beam (micrometers)')
plt.ylabel('Induced Energy Spread (arbitrary units)')
```

```
plt.title('Comparison of Energy Spread Induction by Laser Modes')

plt.legend()
```