Title

Review: Laguerre-Gaussian Mode Laser Heater for Microbunching Instability Suppression in Free-Electron Lasers

Author
Lee, Ryan

Publication Date
2023-12-10

Review: Laguerre-Gaussian Mode Laser Heater for Microbunching Instability Suppression in Free-Electron Lasers

Ryan Lee[1] and Sergio Carbajo[1]

[1]University of California, Los Angeles, Department of Electrical and Computer Engineering

Abstract

This work [1] presents a method to reduce microbunching instability (MBI) within free-electron lasers (FEL) and related devices, through using a Laguerre-Gaussian transverse mode. An examination of using a Hermite-Gaussian mode is also performed.

Introduction

To reduce MBI within free-electron lasers, a Laguerre-Gaussian transverse mode laser heater (LH) is used as opposed to a Gaussian mode. As a result of the spatial geometry of LG modes, they can interact with a laser heater's electron beam without direct overlap, in order to produce an electron beam energy spread with a purely Gaussian distribution. The purpose of this is to reduce MBI due to a more spread-out spatial frequency distribution, in an effort to induce more controlled energy spread instead of relying on severe uncontrolled downstream spread.

In response to this paper's findings, other non-LG modes, such as Hermite-Gaussian (HG) modes, will also be examined with mathematical detail.

Methods

The paper describes an experimental setup that includes a Gaussian-beam producing FEL, a spiral phase plate, a laser heater, and a spectrometer. To examine the MBI of a Gaussian mode laser, the FEL directly lases into the LH, which maps an electron beam inside the beam to induce energy spread in the beam's energy distribution. Testing an LG_{01} LH entails a similar setup, which also includes the spiral phase plate before the beam enters the LH. This converts the Gaussian beam into a LG_{01} beam as a result of the overall spatial phase shift. Both beams are separately measured by focusing into a spectrometer. The resulting spectrometer reading, which maps the sampled energy intensity of the electron beams as a function of frequency, is recorded and used to determine the energy spread based on the fitting Gaussian curve for each measurement.

As an alternative to using LG modes, low-order Hermite-Gaussian modes may also be useful to examine for this application. Similar to the report's experimental LG_{01} mode laser beam, a HG_{10}, HG_{01}, or HG_{11} beam has distinct regions with zero intensity in their intensity distribution plots

[2]. However, unlike LG modes, HG modes are rectangularly symmetrical, so there will be Cartesian-spaced regions on the 2D intensity distribution that deviate from the pure Gaussian produced by LG modes. In Figure 1, the intensities are null along the Cartesian axes for HG_{11}.

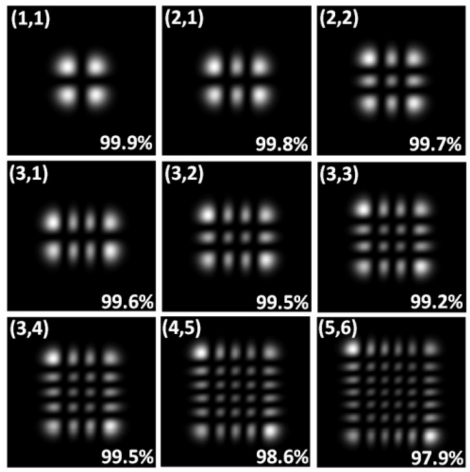

Figure 1: Examples of HG modes, obtained from [3]

As a result, a HG_{11}-excited electron beam will not be purely Gaussian at certain orientations along the direction of propagation of the beam. In effect, the electron beam width may not be as wide near regions with null beam amplitude due to lack of electric field. This can be represented as a low pass filter (LPF) in terms of spatial distribution of the resulting electron beam. Assuming a perfect LPF, which has a Fourier transform as a sinc function, the convolution results in a spectral transform curve that is nearly identical to a pure Gaussian curve.

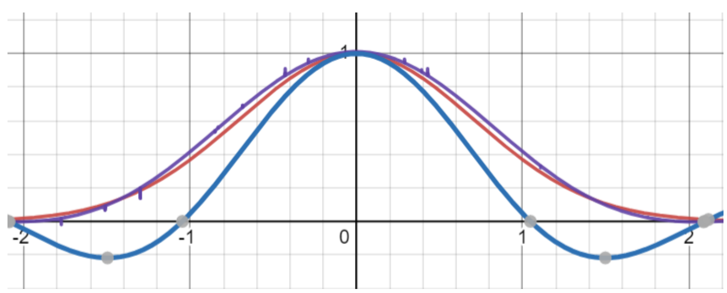

Figure 2: Convolution (purple) of a Gaussian function (red) and a sinc function (blue)

Results and Interpretation

As described in this report, the LG_{01} laser induced energy spread preserved a Gaussian-shaped distribution significantly better than a transverse Gaussian mode input laser. This is especially apparent at higher input power, where the Gaussian mode energy distribution took the form of a double-horn shape. In addition to reducing beamline precision, an analysis of the spectral contribution of both lasers demonstrated a higher potential for MBI energy spread with the Gaussian laser due to its higher spatial frequency components.

From the spectral transform for the Gaussian and sinc functions, it can be concluded that an HG_{11} or similar mode LH will have MBI suppression equivalent to that of the LG_{01} LH, since both have similar electron intensity distribution and a resulting similar spectral signal contribution. Therefore, for applications that benefit from MBI suppression for a more precise beamline, users may choose between a low-order HG or LG-mode LH, depending on other factors like cost and ease of manufacturability.

Conclusions

To reduce energy spread in higher LH power inputs, a LG_{01} mode LH can be used to induce controlled energy spread and less spread downstream due to MBI. A similar spread can be achieved using a HG-mode beam. Other modes can be investigated, either mathematically or empirically, in order to determine if these will have similar effects on MBI suppression. Additionally, altering parameters of the laser, such as wavelength, may contribute to an improvement to the LH beamline, so these can also have promising results.

These findings will contribute to more efficient and precise FEL design, which can result in overall improved laser design for communications and sensing applications.

References

[1] Tang, J., Lemons, R., Liu, W., Vetter, S., Maxwell, T., Decker, F.-J., Lutman, A., Krzywinski, J., Marcus, G., Moeller, S., Huang, Z., Ratner, D., & Carbajo, S. (2020). Laguerre-Gaussian mode laser heater for microbunching instability suppression in free-electron lasers. Physical Review Letters, 124 (13). https://doi.org/10.1103/physrevlett.124.134801

[2] J. Rutledge, M. Stanley, and M. Lo, “Conversions of Transverse Gaussian Laser Modes,” Stony Brook University Laser Teaching Center, 2016.

[2] Shu-Chun Chu, Yun-Ting Chen, Ko-Fan Tsai, and Kenju Otsuka, "Generation of high-order Hermite-Gaussian modes in end-pumped solid-state lasers for square vortex array laser beam generation," Opt. Express 20, 7128-7141 (2012)