Title

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

Author
Hassani, Abbas

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

Abbas Hassani[1]

[1]Student in University of California, Los Angeles, Electrical and Computer Engineering 170A Principles of Photonics

abbas1996@g.ucla.edu

Abstract. —This review explores Bessel beam methods for generating donut-shaped intensity beams with fixed polarization, focusing on their application in Free-Electron Lasers (FELs). It examines the potential of non-Laguerre-Gauss modes and assesses the impact of modifying laser parameters, such as wavelength, on the performance of FELs.

Introduction. —Free-electron lasers (FELs) are pivotal in numerous scientific applications, providing high-intensity, coherent radiation [5]. A key challenge in FEL operation is suppressing microbunching instability (MBI), typically addressed by introducing an energy spread within the electron beam using a laser heater [5]. A laser heater is a device used to suppress MBI. It typically includes a short undulator (a device to alter the path of charged particles) within a chicane and an infrared (IR) laser [5]. MBI is a type of disturbance that occurs in particle accelerators. It's caused by the collective effects of a beam of particles, like electrons [5]. MBI is a significant challenge in operating FELs, as it degrades beam quality and impedes performance. LG modes are widely used to mitigate MBI through a laser heater mechanism [5]. The LG01 mode preserves a Gaussian-shaped energy distribution as the laser power increases, which aligns with theoretical predictions. This is contrasted with the Gaussian mode, which at higher energies shows a double-horn distribution, considered less efficient for MBI suppression [5]. The LG01 mode shows better suppression of MBI than the Gaussian mode. This is demonstrated by the lower midinfrared (MIR) spectral signal in the LG01 mode, indicating reduced MBI. The recent interest in producing donut-shaped beams with fixed polarization stems from their potential to improve FEL performance, particularly in reducing microbunching instabilities. A transverse Laguerre-Gaussian 01 (LG01) mode is particularly effective, as it provides a Gaussian-shaped energy distribution, leading to better suppression of microbunching [5]. However, this paper proposes the use of Bessel beams (BBs) for MBI suppression, presenting their unique non-diffracting properties and fixed polarization characteristics.

Methods. —Donut-shaped beams, characterized by their ring-like intensity profiles, are essential in applications requiring precise beam control. One method for creating these beams is through Bessel-Gauss techniques [3][2]. Bessel-Gauss beams are formed by superimposing Bessel functions onto a Gaussian beam, resulting in a central bright spot surrounded by concentric rings [4][1]. By manipulating the phase and amplitude of these beams, the central spot can be minimized, creating a donut-shaped intensity profile [2].

Bessel-Gaussian modes offer unique advantages in FEL applications. Bessel beams, known for their non-diffracting and self-healing properties, are particularly useful in maintaining beam coherence over longer distances. This feature benefits FELs where beam stability is critical [1]. In the cylindrical coordinates, the complex amplitude for the nth-order Bessel beams can be expressed as [1]:

$$E_n(r,\varphi,z) = Ae^{ik_z z} j_n(k_r r) e^{\pm in\varphi}$$

Where A is the complex constant, k_z = $k\sin\theta_0$, k_r = $k\sin\theta_0$, $k=2\pi/\lambda$ is the wavenumber and λ is the wavelength of the light radiation, θ_0 is the angel of the conic wave to the z-axis. The function $j_n(x)$ is the nth order of Bassel function the first kind. The zero-order beam E_0 has a maximum intensity on the axis, like the Gaussian beam (GB); but, unlike the GB, it also has a collection of circular nodes ringing the axis [1].

Figure1 [1].

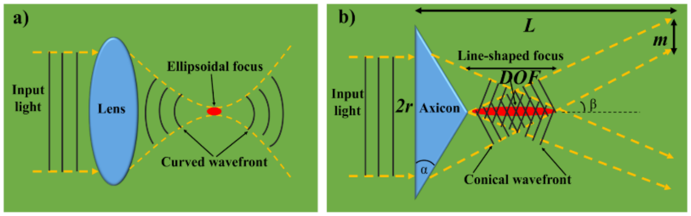

Figure 1. An illustration shows the creation of Bessel Beams (BBs) using Gaussian beams: (a) A Gaussian laser beam, when focused by a lens, forms an ellipsoidal focus, turning plane waves into a curved wavefront; (b) BBs are produced using an axicon, which creates a conical wavefront and a central lobe, forming a line-shaped focus [1]. By passing Gaussian or Laguerre–Gauss beams through an axicon, a conical lens, they are transformed into zeroth-order or higher-order BBs, as the axicon bends all wavefronts at a fixed angle [4].

We will let α denote the opening angle of the cone, so all wavevectors in the beam are at angle α from the z-axis. $\tan\alpha = \frac{|k_r|}{k_z}$

Figure 2 [4].

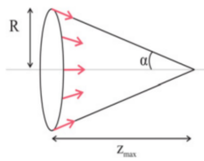

Figure 2. The wavevectors for a Bessel beam lie on a cone of opening angle $\alpha = tan^{-1}\frac{R}{Z_{max}}$. The lens's aperture angle, R, and the maximum distance of wave propagation, z_{max} , are key factors. Wavefronts, perpendicular to wave vectors, create Bessel beams through interference, appearing as a single-ring pattern in the far-field due to their narrow angular spectrum [1]. While creating a true Bessel Beam (BB) requires infinite energy, an axicon closely mimics this with its nearly non-diffracting properties within its depth of focus (DOF) [1]. DOF depends on the beam's radius entering the axicon (r), the axicon's refractive index (n), and the alpha angle (α) [1].

$$\text{DOF} = \frac{r\sqrt{1-n^2 sin^2\alpha}}{sin\alpha cos\alpha(n cos\alpha - \sqrt{1-n^2 sin^2\alpha}} \approx \frac{r}{(n-1)\alpha}$$

The basic equation assumes that the angle of refraction is small and becomes less accurate as α decreases. Beyond the axicon's *DOF*, a ring of light is produced. The thickness of the ring (*m*) remains constant and is comparable to r [4]:

The fundamental equation is based on a small angle of refraction and loses accuracy with decreasing α. Outside the axicon's depth of focus (DOF), a light ring forms, with its thickness (m) remaining constant and like r [4]:

$$m = \frac{r\sqrt{1-n^2 sin^2\alpha}}{sin\alpha cos\alpha(n cosa - \sqrt{1-n^2 sin^2\alpha}} \approx r$$

A laser beam with the desired wavelength and polarization is directed through an axicon, a conical lens that transforms a Gaussian beam into a Bessel beam [4]. The apex angle of the axicon is carefully selected to match the required cone angle for the Bessel beam, which determines the diameter of the central non-diffracting region. A spatial filter is placed at the focal plane of the axicon to remove any undesired Gaussian components, ensuring a pure Bessel beam profile. The intensity distribution of the Bessel beam is captured using a Charged Coupled Device (CCD) camera at various distances from the axicon or aperture to verify the non-diffracting nature. A polarimeter is used to confirm the polarization state of the Bessel beam. Fixed polarization is crucial for consistent interaction with the electron beam in the FEL [1].

The Bessel beam is aligned coaxially with the electron beam in the FEL using precision mirrors and beam steering systems. The Bessel beam's intensity distribution is used to induce a controlled energy spread in the electron beam. Parameters such as the axicon angle (or aperture size) and laser power are fine-tuned to achieve the desired energy modulation [1].
The performance of laser heaters in FELs can be enhanced by modifying various laser parameters. Wavelength adjustments, for instance, can influence the interaction between the laser and the electron beam, potentially leading to more efficient suppression of microbunching instabilities. Shorter wavelengths enhance resolution but require precise control systems to manage diffraction limits and beam focusing [6].
Additionally, manipulating the beam's polarization can affect its absorption and interaction with the electron beam. Exploring circular or elliptical polarizations could yield new dynamics in energy spread distribution within the electron beam [1], possibly enhancing the suppression of instabilities.
Spatial Light Modulators (SLMs) are pivotal in dynamically modifying the phase and amplitude of laser beams, enabling the creation of complex profiles like Bessel modes [1][5]. Tunable lasers are essential for exploring the effects of different wavelengths on FEL performance. Pulse shapers and polarization controllers are also crucial. These devices allow for the precise control of the laser's temporal and polarization characteristics, respectively, enabling researchers to experiment with various beam properties and their effects on FEL performance [1].

Conclusion. —This review underscores the significant potential of Bessel beam methods in enhancing Free-Electron Laser (FEL) performance, particularly in mitigating microbunching instabilities. By exploring the unique characteristics of Bessel beams, such as their non-diffracting nature and fixed polarization, this study illuminates alternative approaches to the traditional Laguerre-Gauss modes. The implementation of Bessel beams, created through the manipulation of Gaussian beams using an axicon, demonstrates the capability of these beams to maintain coherence and stability over extended distances, a crucial factor in FEL operations. Additionally, the review highlights the importance of fine-tuning laser parameters like wavelength and polarization to optimize FEL performance. Advanced technologies like Spatial Light Modulators, tunable lasers, pulse shapers, and polarization controllers play a pivotal role in realizing these sophisticated beam-shaping techniques. This research not only contributes to a deeper understanding of beam dynamics in FELs but also opens new avenues for future exploration and technological advancements in laser physics and applications.

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