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Publication Date

2023-12-11

Alternate techniques of Guassian shaping for E-Beams in FELS

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1 Abstract

A Laguerre-Gaussian 01 laser heater forms a Gaussian-shaped energy distribution of electron beams in free-electron Lasers. This paper proposes techniques of 0th-order Bessel beam LH modulation with potential performance benefits to the electron beam.

2 Introduction

The article [7] discusses a mechanism to control and suppress microbunch instability (MBI) with the use of a laser heater (LH) with a transverse Laguerre-Gaussian 01 (LG_{01}) mode in free-electron lasers (FELs). FELs are powerful tools in various scientific fields and form from electron beams that have undergone magnetic compression. This process can compromise the quality of the electron beam, decreasing the quality and performance of the FEL. A LH can introduce some energy spread amongst the electron beam which can combat the affects of MBI. Recognizing that achieving a Gaussian transverse distribution can suppress MBI, a LG_{01} mode LH is introduced as a potential mechanism to creating the optimal distribution.

In this experiment, the researchers use a spiral phase plate to convert the LH transverse profile from Gaussian to the LG_{01} distribution. This leads to zero amplitude of the electric field at the laser's center. The LG_{01} mode LH must be positioned in such a way that the electron beam is at the center of the laser in order for the Gaussian distribution of the beam to be generated. A spectrometer placed downstream of the LH measures the induced energy spread.

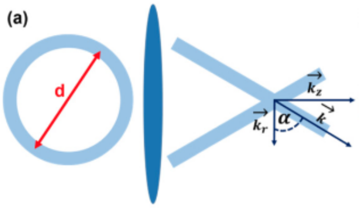
Researchers are able to quantify results of the LG_{01} mode LH on the induced energy spread of the electron beam by fitting the induced energy data points to Gaussian distributions at various laser energies. The result of the data fitting reveals that the LG_{01} mode LH does in fact induce a more Gaussian-shaped energy distribution compared to the conventional Gaussian mode LH. Researchers also use a midinfrared spectrometer to characterise microbunching at high longitudinal-space frequencies, which show a reduction in microbunching for the LG_{01} mode LH.

The authors extend their results to the role of LH in spatial shaping of soft x-ray self-seeded FEL emission, demonstrating improved monochromaticity and brightness. This research demonstrates that the use of a LG_{01} mode LH can suppress MBI and improve FEL performance.

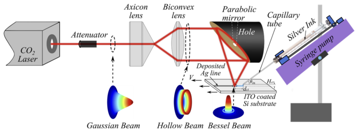
3 Experiment Analysis

In this section, we analyze the specific causes of MBI and why researchers in [7] use a LH to counteract it. The MBI of the electron-beam quality is caused by longitudinal space charge and coherent synchrotron radiation. According to [4], lasers are always spatially and temporally coherent and laser oscillation takes place along the longitudinal axis in order to carry sufficient gain in one direction. For a laser to possess enough beam strength in the longitudinal direction, photons emitted in directions other than the longitudinal must not gain enough energy to have any gain and the photons emitted in the longitudinal direction must obtain regenerative amplification.

Longitudinal space charge arises from the electrostatic repulsion between charged particles within an electron beam as they travel along the longitudinal direction. The primary cause of longitudinal space charge is the fact that particles in the beam carry like charges and thus experience mutual repulsion. Longitudinal space charge may create oscillations on axes other than the longitudinal axis and cause beam expansion, energy spread and MBI.



(a) Formation of a Bessel Beam J_0 using annular illumniation with a singular ring [6]



(b) Example of a configuration of Bessel-Gaussian Beam formation from [3]

Coherent synchrotron radiation is a phenomenon that occurs when particles move along a curved trajectory and emit synchrotron radiation in a coherent manner. Synchrotron radiation is the electromagnetic radiation emitted by charged particles when they are accelerated or deflected by magnetic fields. Coherent synchrotron radiation compromises the spatial and temporal coherent quality required of an FEL and leads to MBI [5].

[7] uses a LH to suppress MBI because it can control the longitudinal phase space of the LH, maintaining the qualities of coherence and longitudinal oscillations required of a laser [2]. A LH introduces controlled energy modulations into the electron bunch, effectively smoothing out the undesired microbunching. By carefully adjusting the parameters of the LH, such as its intensity and frequency, the induced energy modulations can counteract the natural micro-bunching, leading to a more stable and higher-quality electron beam [7].

The article [7] mentions that previous techniques used a Gaussian-shaped LH. A Gaussian-shaped LH is used because it provides a smoothly varying intensity profile which helps to avoid sharp discontinuities that causes instabilities in the electron bunch. It does have some disadvantages including the appearance of double-horn energy distribution, which is why the paper investigates shaping the laser with the LG_{01} mode that takes on a donut-shape.

4 Alternative Donut-shaped modes for the LH

An alternate donut-shaped radiation pattern would be a Bessel function of the 0th-order (J_0). The light diffraction pattern from a cylindrical ultrasound can produce the concentric pattern wanted for a 0th order Bessel function shown in Fig 1a. The electric field of the beam is represented by the following equation

$$E(r,z) = A_0 J_0(k_r r) esp(ik_z z) \tag{1}$$

where A_0 is the amplitude of the electric field, k_r is $kcos\alpha$, k_z is $ksin\alpha$, and α is $tan^{-1}(2f/d)$. The central spot size is

$$\Delta x = 4.81 f\lambda/2\pi d \tag{2}$$

where f is the focal length. The propagation distance is

$$z_{max} = 2fR/d \tag{3}$$

[6]. The beam waist of the Guassian profile in the paper is 100 μm, the beam waist of the LG_{01} is 325 μm and the transverse electron beam size is 50 μm in [7]. In order to ensure that the electron beam is located at the center of the laser for the J_0 mode, we strive to find values of f, λ and d that produces a transverse electron beam size of 50 μm. Since Bessel-beams are non-diffracting, we pick a value of λ and d that are on the same order of magnitude. To stay consistent with the article, we will also choose a value of λ in the infrared range. We will then choose a value of R (semi-diameter of the lens), f and d that results in a z_{max} of at least 10 m since the LH undulator length is .5 m. The optimal values are shown in the table 1.

To produce the Bessel Beam J_0 we can use the cylindrical ultrasound or the light can pass from the IR drive laser to an axicon lens, then through a Biconvex lens and a parabolic mirror that will form a Bessel-Gaussian beam [3]. A demonstration of this technique is in Fig. **??**.

One downside of this method is that the polarization of the LH may not be linear after the generation of the Bessel beam. A linear polarization is crucial for for the electron beam to take on a Gaussian distribution. We therefore propose another method of generating the Bessel beam which is insensitive to polarization and

f	65 μm
λ	1 mm
R	7.6 m
d	1 mm

Table 1: Values of Bessel Beam LH to find a transverse electron beam size and propagation distance that is consistent with the figure.

can hold either a circular or linear polarization from the incoming wave. This technique makes use of metasurfaces, two-dimensional arrangements of medias that have the ability to be designed for different applications that can introduce abrupt phase-change across the media (up to $2pi$, just like in [7]). The metasurface would be placed at a sufficient distance in front of the electron beam so it sees a plane wave. To generate a 0th-order Bessel Beam, the metasurface must be designed with a phase profile that varies in the radial direction. If the incoming beam is in the infrared range, say 800 nm, and we want our beam width to be the same as that from the [7] (325 μm) according to the following equation: $FWHM_{J_0} = .385\ \lambda/(\mathrm{NA})$. The numerical aperture (NA), or the quantity that quantifies the light gathering ability of the metasurface, must be .0009 according to [1]. This NA is very small and as [1] performs experiment with an NA of about .7, this new system would have to decrease the output wave's beam-width to the nm scale. This can be an advantage as smaller beam-widths have less beam divergence and higher gain but also has disadvantages as narrower beams are more unstable and sensitive to environmental factors [4]. One should also note that within the infrared range, the longer wavelengths will propagate farther than the shorter wavelengths [4]. In [7] the length of the system is fairly long so a longer wavelength should be preferred to ensure that the electron beam can propagate far enough.

5 Conclusion

This paper concludes that a 0th-Order Bessel Beam LH can be an appropriate alternative to a $LG_(01)$ mode LH, if designed properly, with the goal of decreasing MBI of an electron beam in FELs. In the future, the different methods of forming a 0th-Order Bessel Beam LH should be studied and analyzed in a lab setting.

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