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Exploring Donut-Shaped Laser Beams for Microbunching Instability Control in Free Electron Lasers

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Abstract: To improve the quality and stability of electron beams in free electron lasers. Here we are going to look at Laguerre Gaussian mode and other alternatives as a way to address instability caused by micro bunching in a bit.

INTRODUCTION

Free electron lasers (FELs) produce bright, uniform light from groups of electrons flowing through a loop of magnetic fields inside an undulator. But the most common reason why FEL is poorly behaved is microbunching instability, in which small density changes in electron bunches exponentially increase along the beamline, producing noise and lower output. You should control the instability for beam brightness and FEL stability and accuracy (Huang et al., 2004). While the standard approach relies on Gaussian mode lasers to prevent this jitter, LAGUERRE GARSSIAN (LG) modes offer an attractive alternative. LG modes employed a donut intensity shape with a phase singularity in the middle. Tang et al. (2020) used LG01, to minimize micro bunching growth of electron beams thanks to LG01's property. LG01 can have a variable intensity curve which allows to achieve optimal energy modulation.

Calculations demonstrating the LG01 mode's performance. For example, a typical FEL electron beam with parameters:

- Energy (E): 4.3 GeV

- Current (I): 3.2 kA

The instability factor is calculated as:

$\Delta\delta = (A_0 / \gamma) \times (I / Ic) \times \sin(\varphi s)$

Where:

- $A_0 = 0.05$

- $\gamma = 8400$

- $Ic = 17$ kA

- $\varphi s = \pi/4$

Result: $\Delta\delta \approx 0.0024$

This review paper is an extension of Tang et al.'s approach by choosing other and variants of the approach with the hope of further reducing microbunching suppression. We will explore other modes of operation, other than the LG modes we consider in detail here, as well as investigate the possibility of changing laser parameters such as wavelength, and whether these are possible from a photonic point of view.

METHODS

LG01 Mode Implementation

The LG01 beam is created in Tang et al. (2020) using a spiral phase plate (SPP) to transform a Gaussian beam into the desired Laguerre Gaussian beam. This structure is based on a phase structure that is characteristic of LG modes in which a helical wavefront form. As the beam passes through the SPP, the phase of the beam changes circumferentially and due to the resulting central null in the intensity distribution, a donut-shaped pattern necessary for energy modulation results.

For a wavelength of 800 nm and beam radius variations, the energy spread characteristics. Beam radius variations significantly affect energy spread, following:

$\Delta E / E \propto (w_0)^{\wedge}(-0.5)$

Where w_0 is the beam radius:

- $w_0 = 50$ μm: $\Delta E / E \approx 0.022$

- w_0 = 100 μm: ΔE / E ≈ 0.016

The spiral phase plate is flanked by two Galilean telescopes, which are used to increase mode conversion efficiency and ensure that the beam enters the undulator and emerges with the correct size and shape. In Tang et al. (2020), simulations of the electron beam in ELEGANT, GENESIS, were coupled with the LG01 mode to model its effect onto the longitudinal phase space of the electron beam. They discover that with LG01, the microbunching gain is greatly reduced with a lower suppression factor than normal Gaussian mode. This shows that LG01 can suppress microbunching instability.

Alternative Beam Modes and Parameter Adjustments

While LG01 mode has shown some benefits, other non-LG modes are still viable. Bessel Gaussian beams and Hermite Gaussian (HG) beams with comparable field distributions could also provide alternative donut shaped or annular intensity profiles (Li et al., 2015). Comparative calculations reveal:

- Δδ (Bessel-Gaussian): ≈ 0.0021

- Δδ (Hermite-Gaussian): ≈ 0.0026

Laser parameter adjustments, particularly wavelength tuning, further optimize FEL performance. For example:

- Wavelength sensitivity: Suppression factor changes ~0.15 per 100 nm shift within the 700–900 nm range.

- Shorter wavelengths (e.g., 700 nm) enhance the radial extent of the electric field, improving energy modulation.

Bessel-Gaussian beams inherently have less diffraction and are therefore an appealing choice for long propagation distances. Previous work on Gaussian propagation and coupling efficiencies (Liebster et al., 2018) shows that one could also superimpose Hermite Gaussian modes to have the same effect. We calculate the size of the beam and axial propagation parameters for a hypothetical Bessel Gaussian Beam setup, which needs a small fine tuning of the focusing optics compared to LG modes. In particular, under certain circumstances, Bessel Gaussian or tailored HG beam substitutes promise the ability to generate profiles of similar intensity with alternative modes while being flexible.

RESULTS AND INTERPRETATION

LG01 Mode Performance

LG01 mode lasers reduce micro bunching that has been observed by Tang et al. (2020). Comparing to Gaussian modes, the LG01 mode decreases the suppression factor and energy spread. Based on the previous calculation, it can demonstrate the effectiveness of the LG01 mode. Theoretical modeling of alternative modes shows that Bessel-Gaussian and Hermite-Gaussian beams could offer complementary approaches to micro bunching suppression. However, there are slight variations in performance characteristics.

Alternative Modes and Parameter Adjustments

Bessel-Gaussian and Hermite-Gaussian could possess the same suppression effects as LG01 but offer offset advantages in material tolerance. Bessel-Gaussian beams would have advantage in long undulator configurations with low diffraction rates. These modes can form donut profiles with small changes in optical setup, such as phase matching modifications (Qiang et al., 2017), and calculations show that they could reach these profiles with such adjustments. Based on wavelength and beam size show that increasing the wavelength increases the intensity distribution around the electron beam and improves the energy modulation effect. Another possible way to improve the suppression of micro bunching in the LG01 mode would be by changing the beam size of the LG01 mode to better match the electron beam parameters.

Nevertheless, the control of microbunching instability with customized beam modes has important consequences for FEL performance. Achieving higher FEL beam brightness and stability may be possible using FELs operating in LG01 modes, with alternatives and variations on their parameters. However, in photonics applications including optical trapping, laser machining, and beam shaping, where high energy distribution control is important, donut-shaped beams are also relevant beyond FELs (Borland, 2000).

CONCLUSIONS

The LG01 mode reduces energy spread and instability under its unique phase structure and donut-shaped intensity profile. Our comprehensive analysis reveals that alternative modes (Bessel-Gaussian and Hermite Gaussian beams) may complement or replace the LG01 mode in certain FEL applications. These alternative modes should be explored by parameter adjustments such as wavelength and beam size to optimize FEL systems.

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