Title

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

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

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Abstract

This article focuses on exploring an array of discrete beamlets as an alternate beam profile to suppress MBI effects in free-electron lasers in comparison to the Laguerre-Gaussian 01 (LG01) profile. It examines the resulting transverse profile, and compares the pros and cons of each beam type.

INTRODUCTION

Free electron lasers (FELs) are a powerful source of hard x-rays, supporting wavelengths as short as 1 Å [2]. Their quality is degraded by microbunching instability (MBI), which can be suppressed through laser heaters (LH) suppressing unwanted energy modulations [3]. The effectiveness of the LH is largely dependent on the transverse profile of its beam as it impacts the resulting energy distribution of the FEL, where Gaussian-like profiles lead to the most desirable result. Under ideal conditions, the Laguerre-Gaussian 01 (LG01) mode outperforms a singular Gaussian profile, resulting in better MBI suppression and flexibility [3].
However, the LG01 mode also suffers from drawbacks, such as transverse jitter, which motivates finding alternate beam profiles. One approach is to use a beamlet array, or multiple Guassian beams. This allows different electrons to experience different modulation amplitudes, and offers more freedom in design [1].

METHOD

The basic idea behind MBI suppression lies in a laser heater modulating, thus increasing the energy spread of the beam. The paper explores the use of the LG01 profile to do so in order to avoid the double-horned energy distribution that results from a singular transverse-Gaussian beam at higher energy.
The intensity distribution of a Gaussian beam can be given by the Eq (1).

$$I(r,z) = I_{max} e^{\frac{-2r^2}{w^2}} \quad (1)$$

$$I_{max} = \frac{P_0}{0.5\pi w^2} \quad (2)$$

The intensity of the beam varies with each position from the laser, where, w is dependent on z. Thus the transverse energy distribution of the laser heater is critical in modulating the e-beam to suppress MBI accumulation. The beam profile of the LG01 mode is a donut-like pattern, with the highest intensities in a ring around a dark center.
The paper reveals the LG01 maintains a transverse-Gaussian energy profile even at high energies, and energy spread on par with a Gaussian beam. Furthermore, the intensity of the beam is highly concentrated at a singular relative photon energy, and thus the high level of monochromaticity also indicates strong sideband suppression. However, the LG01 mode is also highly susceptible to transverse jitter [1]. Despite being a strong candidate to suppress MBI instability, for inconsistent e-beams, this is a large drawback in effectiveness that can be addressed through exploring other beam profiles.

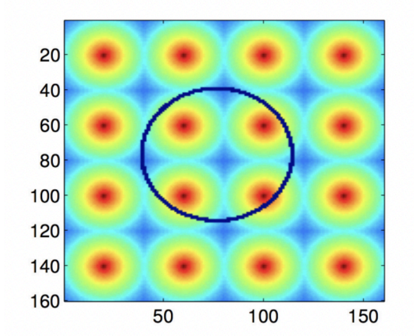

Figure 1. Square Beamlet Array Pattern (Ref. [1])

An alternative to the LG01 mode could be an array of Gaussian beams instead. Multiple beamlets can be arranged in an array at different spacings, patterns, and intensities. Each beam is then modulated in amplitude to vary the energy received by each electron, following Eq. (3).

$$E(0,t) = \hat{e}|E(t)|e^{i\phi_E - iwt} \tag{3}$$

The complex response to the modulating amplitude can be represented by a frequency-dependent constant m, where the output electrical power R(f)$\propto m^2$. To suppress MBI, however, the energy distribution of the beamlet array must be derived to follow a Guassian profile.

The probability distribution of a laser profile, or energy distribution, where δ is the energy modulation an electron receives based on Fig. 1 is represented by Eq. (5), where $R(\eta, \delta)$ is the probability density function of a sine wave, normalized to 1 [1].

$$P(\delta) = \int_{\delta}^{\infty} Q(\eta)R(\eta,\delta)d\eta \tag{4}$$

$$R(\eta,\delta) = \frac{2}{\pi\eta\sqrt{1-\frac{\delta^2}{\eta^2}}}, \quad \int_0^{\eta} Rd\delta = 1 \tag{5}$$

Then an intensity distribution $Q(\eta)$ is chosen to result in a Gaussian energy spread. The LG01 intensity distribution follows Eq. (6), where A is a normalization constant [2]. Based on the LG01, intensity distribution is chosen to match, and the final energy distribution described in Eq. (8) is theoretically Gaussian, where δ and σ_r are the energy spread and fill radius respectively, and can be optimized experimentally [1].

$$h(r) = Ae^{\frac{-r^2}{2\sigma_r^2}} \tag{6}$$

$$Q(\eta) = \frac{\eta}{\sigma_r^2}e^{\frac{-\eta^2}{2\sigma_r^2}} \tag{7}$$

$$P(\delta) = \sqrt{\frac{2}{\pi\sigma_r^2}}e^{\frac{-\delta^2}{2\sigma_r^2}} \tag{8}$$

In practicality, their shape is more Lorentzian than Gaussian, and energy distribution is optimized to full-width half-magnitude (FWHM) for consistent and effective heating [2].

RESULTS

Following the equations above, Figure 2. reveals a theoretical energy distribution very similar to a Gaussian curve. As such, a beamlet array would be successful in MBI suppression.

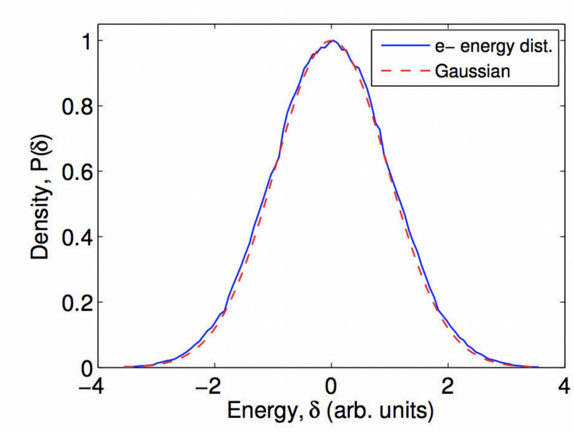

Figure 2. Energy Distribution vs Energy Modulation of Beamlet Array (Ref. [1])

While singular Gaussian and LG01 beams require precise optimizations in transverse offset jitter, beam size, and tilt angle, the beamlet array is more consistent and insensitive to variations in these parameters [2]. The flexibility of its arrangement in symmetry and larger surface area help minimize the effect of these variations in the final energy distribution after the LH. Studies in practicality have discovered the profile to result in MBI suppression that isn't as strong, but its power stability makes it a robust alternative [2].

A key issue with the beamlet array configuration, however, is at higher beamlet radiuses, the resulting energy distribution separates into two peaks instead of one, and thus is ineffective at MBI suppression [2].

CONCLUSION

An array of discrete Guassian beams is an alternative to the Laguerre-Gaussian 01 (LG01) mode for suppressing MBI in FELs. By analyzing its amplitude and energy modulations, it discovered that the final energy distribution mostly matches a Gaussian profile like the LG01 mode, and thus can suppress MBI. Though not as effective as the LG01 mode, its consistency across laser and e-beam variations, such as jitter and tilt, make it a valid alternative. Since the final equation for energy distribution is dependent on energy spread, it is also possible to optimize δ for MBI suppression accordingly.

The Guassian beamlet array is thus an effective option for systems with inconsistent e-beams, and addresses a critical weakness of the LG01 mode against transverse jitter. This includes non uniform or changing e-beams, whether each beamlet can be optimized in both size and power to respond to such changes while maintaining heating efficiency. Thus, while some of the strength of MBI suppression is lost, the flexibility of this beam profile also allows more flexibility in its application.

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