Laguerre-Gaussian Mode Laser Heater Beam Size for Microbunching Instability Suppression in Free Electron Lasers

Charles, Christophe

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Christophe Charles

Undergraduate student, Department of Electrical and Computer Engineering, UCLA

christophejc24@g.ucla.edu

Abstract: Microbunching instability (MBI) is known to be detrimental in degrading free-electron lasers (FELs). One way to suppress such instabilities is through the use of a laser heater (LH) with manipulated transverse energy distributions, such as the Laguerre-Gauss mode [2]. However, independent of the energy distribution of the LH, there are other factors that can further contribute to overall MBI suppression. This factor can be defined through the I integral, a measure of how well the LH suppresses the MBI [1]. Here, we will present the relationships that define the suppression factor given the Laguerre-Gauss mode and investigate the threshold for heightened stability by decreasing the I integral through manipulating the LH to FEL spot size factor.

INTRODUCTION

Free electron lasers (FELs) are a type of laser that uses a high-energy electron beam (*e* beam) to produce light that is both coherent and high intensity. These *e* beams can degrade longitudinally due to microbunching instability (MBI) [2]. This is an effect that can detrimentally increase the gain of the e-beam, which can create uncertainty in the gain process. MBI is observed when the *e* beam experiences uncontrolled modulations in longitudinal density and spacing. This instability creates unknown conditions that can impact the overall repeatability of certain experiments. One common solution is the use of laser heaters (LH) that have the ability to control this instability through MBI suppression. The LH can induce an energy spread to the e-beam at the initial state that will allow for less MBI in the latter phases of measurement. This means that with an initial induced energy spread on FELs from a LH, the final energy spread can be decreased.

The focus of the experiment in [2] shows MBI suppression can be increased when using a Laguerre-Gaussian$_{01}$ (LG$_{01}$) mode laser heater as opposed to a Gaussian mode laser heater. While the experiment explains that the effectiveness of a LH can highly depend on the energy distribution shape and positioning of the LH, we will focus on the physical factors that can be manipulated to change the suppression factor. Because the I integral is the representation for microbunching gain, we will examine ways in which we can minimize this factor regardless of the shape of the LH, specifically in the LG$_{01}$ case. This can be accomplished through manipulating the ratio between the transverse LG$_{01}$ mode laser size and the initial *e* beam size.

In manipulating the transverse laser size to beam size ratio, we find diminishing returns after increasing it over a certain threshold. In [1] we find that when the ratio is 3, the LG$_{01}$ mode is better than a matched Gaussian (ratio = 1) by a factor of 3. As this ratio reaches 3.5, the I integral starts to flatten, making it meaningless to further increase the ratio (FIG 1). In [2] this ratio is 6.5, but some of the parameters are different from the simulation in [1]. In this review, we will find the relationship between the I integral and the transverse laser size to *e* beam size ratio to determine the threshold for when it would be beneficial to change the ratio to either save power (decreasing laser spot size) or increase MBI suppression (increasing laser spot size).

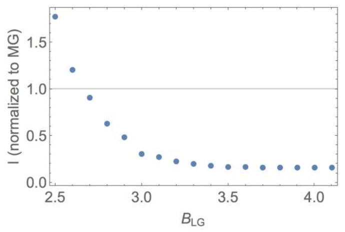

FIG. 1. LG laser profile I integral as a function of B_{LG} [1]

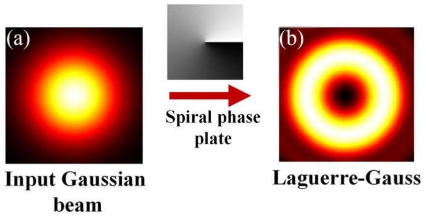

FIG. 2. Simulation of (a) input Gaussian beam, (b) LG after passing through spiral phase plate [6]

METHODS

Through experimentation in [2] comparing the use of a LG_{01} mode laser heater and a more commonly used Gaussian mode laser heater, it is found that the LG_{01} mode induces a Gaussian energy spread that more effectively suppresses MBI in FELs.

With the given LCLS FEL, the experiment in [2] first uses a spiral phase plate (SPP) to convert the Gaussian mode LH to a LG_{01} laser mode (FIG 2.) [6]. Then, this "new" LH induces an energy spread onto the FEL which modulates and increases the energy spread of the *e* beam. This initial increase suppresses the downstream MBI [2]. After this induced energy spread, there are two diagnostics used to quantify the MBI suppression.

The first diagnostic is a 135MeV spectrometer that measures the relative energy spread after heating. The more this energy spread resembles a Gaussian energy distribution and not a double-horned distribution, the higher the potential is for better microbunching suppression [2]. The second diagnostic is a mid-infrared spectrometer that characterizes microbunching from the coherent emission of the *e* beam. From this, the radiation profile is proportional to the overall bunching factor[2].

The experiment in [2] ultimately found that in the diagnostics, the LG_{01} shows better MBI suppression in both the 20-30keV and 15-20 keV range. Concluding that the energy distribution of the LH affects suppression of MBI, and the LG_{01} mode LH shows improvement on MBI suppression compared to the Gaussian mode LH.

Taking the case of the LG_{01} mode. The equation for the I integral is a measure of the microbunching gain (G) (Eq. 1) integrated over the wavenumber (k_0) (Eq. 2) [1, 3].

$$G = \frac{I_0}{\gamma I_A}\left|k_f R_{56}\frac{4\pi Z(k_0)}{Z_0}\right|S(k_f) \quad (1) \qquad I = \int_0^\infty G^2(k_0)dk_0 \quad (2)$$

Where the smaller I, the better the laser heater suppresses the microbunching gain [3]. Here I_0 is the initial peak current, I_A is the Alfven current, γ is the *e* beam energy spread, k_f the compressed modulation wave number through compression, Z(k) is the longitudinal space charge impedance defined below (Eq. 3), and S_L is the gain suppression (Eq. 4)[1, 3].

$$Z(k) = \frac{iZ_0}{\pi k r_b^2}\left[1 - \frac{kr_b}{\gamma}K_1\left(\frac{kr_b}{\gamma}\right)\right] \quad (3) \qquad S(k) \approx e^{-k^2R_{56}^2A^2} \quad (4) \qquad A = \left(1 + \frac{2}{B_{LG}^2}\right)\sigma_\delta \quad (5)$$

Where Z_0=377 Ω, K_1 is the undulator strength parameter, and r_b is the radius of the transverse cross section, and A is the normalization factor for intensity for LG_{01} (Eq. 5) [1]. From this normalization factor, $R = r / \sigma_r$ and $B_{LG} = \sigma_r / \sigma_x$ [1]. B_{LG} is the factor we will look to manipulate as it is the relationship between the *e* beam spot size σ_x and LG_{01} laser beam spot size σ_r.

In our investigation, we will look to find the I integral over the scope of values for B_{LG}. Substituting Eq. 5 into Eq. 4, the suppression factor is given by

$$S(k) \approx e^{-k^2R_{56}^2\left(\left(1+\frac{2}{B_{LG}^2}\right)\sigma_\delta\right)^2} \quad (7)$$

From this we can consider the $k^2R_{56}^2$ as a constant since we are looking to vary B_{LG}. Given that the wavelength of the FEL is constant and the induced energy spread is assumed to be between 20-30keV for optimal MBI suppression [2] , we can vary this based on B_{LG}. Because the I integral will ultimately be characterized by how the suppression factor will vary by B_{LG}, since the ratio is not dependent on the wavenumber, we will judge when this exponential relationship begins to "flatten" [1]. Because the final gain is dependent on the suppression factor, when this value flattens the total gain levels. From that spot size ratio where flattening starts to occur, there are diminishing returns on MBI suppression as the spot size ratio increases.

Using some of the relevant LH and LCLS parameters from [1,2,4,5] (Table 1), we can plot the normalized suppression factor where the MBI suppression increases and flattens out at a particular spot size ratio (FIG 3.).

TABLE 1. Relevant Parameters.

Parameter	Symbol	Value
Transverse electron beam size	σ_x	50 μm
Transverse LG01 mode laser size	σ_r	325 μm
LH included energy spread	$\sigma_\delta mc^2$	20keV
Momentum Compaction	R_{56}	45mm
FEL wavelength	λ_r	1.5 Å

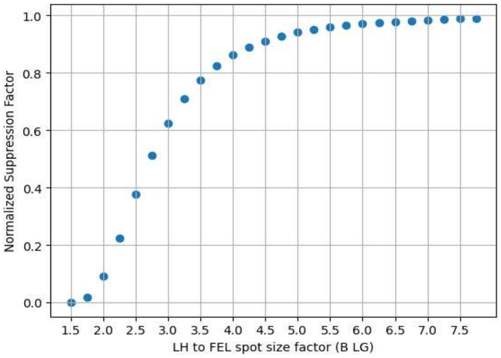

FIG. 3. Normalized Suppression Factor vs. B_{LG}

RESULTS AND INTERPRETATION

From the plotted relationship in Figure 1, we see that the theory is consistent with what was observed in [1] for LG_{01} laser modes—when the spot size ratio between the LH and FEL increases, MBI is better suppressed. The observed suppression starts at nearly zero when B_{LG}=2 and appears to begin to flatten out around at the B_{LG} values between 5-6. This effectively shows when the LG_{01} mode spot size is around the size of the *e* beam (B_{LG}=1.5), it is effectively useless in MBI suppression. As B_{LG} begins to increase, the MBI undergoes increasing suppression until around B_{LG} = 4 when this suppression increases with diminishing returns. This means that the spot size ratio chosen in the experiment from [2] is an ideal size for optimal MBI suppression as B_{LG}=6.5. Because spot size of the LH indicates the power used, it could be beneficial to use less power by decreasing the size at the expense of the MBI suppression, or vice versa depending on the expectations of an experiment.

CONCLUSIONS

In this paper review, we have considered the effect that the LH to FEL spot size factor (B_{LG}) has on MBI suppression in the case of an LG_{01} laser heater mode. We have determined that for this particular mode, increasing the LH to FEL spot size factor can further help with MBI suppression. We also investigated some of the other factors and indicators that quantify MBI, such as total gain (G), the I integral, and suppression factor. Based on the given constraints or the requirements of the output, whether that be nearly complete suppression or half suppression, manipulating the spot size factor (B_{LG}) can be an additional way to further suppress the MBI for improved FEL performance.

REFERENCES

1. Li, S., Fry, A., Gilevich, S., Huang, Z., Marinelli, A., Ratner, D., & Robinson, J. (2015, August). Laser Heater Transverse Shaping to Improve Microbunching Suppression for X-ray FELs. In *Proceedings, 37th International Free Electron Laser Conference (FEL 2015)*.

2. Tang, J., Lemons, R., Liu, W., Vetter, S., Maxwell, T., Decker, F. J., ... & Carbajo, S. (2020). Laguerre-gaussian mode laser heater for microbunching instability suppression in free-electron lasers. *Physical review letters*, *124*(13), 134801.

3. See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.124.134801 for methods: simulation and experimental apparatus, which includes Ref.

4. Liebster, N., Tang, J., Ratner, D., Liu, W., Vetter, S., Huang, Z., & Carbajo, S. (2018). Laguerre-Gaussian and beamlet array as second generation laser heater profiles. *Physical Review Accelerators and Beams*, *21*(9), 090701.

5. Huang, Z., Borland, M., Emma, P., Wu, J., Limborg, C., Stupakov, G., & Welch, J. (2004). Suppression of microbunching instability in the linac coherent light source. *Physical Review Special Topics-Accelerators and Beams*, *7*(7), 074401

6. Pradhan, P., Sharma, M., & Ung, B. (2018). Generation of perfect cylindrical vector beams with complete control over the ring width and ring diameter. *IEEE Photonics Journal*, *10*(1), 1-10.