Title

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Publication Date
2023-12-09

Scientific Review of "Laguerre-gaussian mode laser heater for microbunching instability suppression in free-electron lasers"

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ABSTRACT

This is a scientific review of "Laguerre-gaussian mode laser heater for microbunching instability suppression in free-electron lasers".[1] The objective is to analyze the author's' arguments that a Laguerre-Gaussian-01 mode laser heater more effectively suppresses microbunching instability than its Gaussian counterpart.

INTRODUCTION

Free electron lasers (FELs) operate by providing rapid, high brightness and high current beams of light.[2] For this to occur, a bunch compressor is required to amplify the initially small modulation in the electron beam energy, which can negatively impact the FEL in a phenomenon known as microbunching instability (MBI).[1,3] The effects of MBI can be suppressed by using a laser heater (LH) which seeks to increase the energy spread. There are two primary modes of the laser heater that are addressed in this paper: the Laguerre-Gaussian-01 (LG_{01}) mode and the Gaussian mode, of which this paper argues that the former is more effective in suppressing MBI. The area of that paper I chose to focus on was the characteristics of the double horn distribution yielded by the Gaussian mode, and why that energy spread caused ineffective MBI suppression.

METHODS

To compare the effectiveness of each of the laser heaters, the researchers analyzed the energy spread of both the LG_{01} and standard Gaussian. In this paper, the method that researchers used actually create the LG_{01} was to start with a standard Gaussian.[1] From there, they used a phase-manipulating optical element known as a spiral phase plate (SPP) to acquire a high quality LG_{01} beam that has a null in the center of the laser, resembling a "donut shape".[1,4] The "donut shape" of the LG_{01} means that only a fraction of the power of the laser actually goes towards correcting MBI as the power that comes to the electrons is coming from the electric field that comes around, relying on a power leak that overlaps with the electrons compared to the Gaussian laser that has complete overlap with the electrons.

Despite the higher efficiency of the Gaussian mode over the LG_{01} mode, the analytical results of the experiment seemingly favor the LG_{01} mode's performance. To analyze the energy distributions of each, they plotted the Gaussian fits vs relative energy (keV). The desired shape for optimal MBI suppression is the Gaussian curve, and the goal was to find which mode yielded a consistent Gaussian curve at every relative energy.

To quantify the MBI suppression that results from each of these modes, the researchers used another metric: a midinfrared (MIR) spectrometer, which uses a thin film inserted into the e beam and characterizes microbunching at high frequencies. Ultimately, the goal was to find the LH that would detriment the FELs the least, so the researchers confirmed their test methods and metrics by directly looking for indications of increased seeing and harmonic lasing spectral monochromaticity and brightness.[1]

While reading this paper, I was interested in the double horn shape that the Gaussian laser produced–both how it was produced and why the shape leads to poor MBI suppression. To establish a more foundational understanding of how lasers could suppress MBI, background from other papers indicate that selecting the optimal laser heating should look to combat an overly wide energy spread caused by MBI in the first place. Therefore, the laser heater itself should create laser-electron interactions that essentially induces rapid energy modulation at certain frequency, which as a result, would serve as an energy spread that can sufficiently mitigate the impacts of the microbunching.[5]

To dive deeper into the implications of the double horn shape, in another paper by *Z. L. Huang et al.*, they used a Gaussian laser with different parameters and analyzed the energy spread, and also saw a double horn shape.[6] To verify that the unique parameters of the Gaussian laser used in our paper were not the sole cause of the double horn distribution, rather, Gaussian lasers with other parameters like in the second paper would also yield the double horn shape, I calculated the amplitude of FEL energy modulation at a radial position r = 0 using this equation:

$$\Delta\gamma_L(r) = \sqrt{\frac{P_L}{P_0}}\frac{KL_u}{\gamma_0\sigma_r}\left[J_0\left(\frac{K^2}{4+2K^2}\right) - J_1\left(\frac{K^2}{4+2K^2}\right)\right] \times \exp\left(-\frac{r^2}{4\sigma_r^2}\right),$$

Equation 1. Amplitude of FEL Energy Modulation equation.[6] To calculate this value for the gaussian laser given in the paper, I applied the given parameters σ_r = 100 um, K = 1.56, $\gamma_0 mc^2$ = 135 MeV, L_u = 0.5m, r = 0.

For our laser, the maximum amplitude turned out to be 40 keV compared to the 80 keV of the second paper's laser, indicating the distinction between the two lasers while still yielding the double horn shape.

More quantitative analysis can be done to quantify why the double horn distribution does not yield effective MBI suppression, such as using this equation to quantify the results:

$$S_L(A,B) = \int R\,dR \exp\left(-\frac{R^2}{2}\right) J_0\left[A\exp\left(-\frac{R^2}{4B^2}\right)\right] = {}_1F_2\left(B^2; 1, 1+B^2; -\frac{A^2}{4}\right) = \begin{cases} J_0(A), & B \gg 1, \\ \frac{2J_1(A)}{A}, & B = 1. \end{cases}$$

Equation 2. This equation yields a value known as gain suppression factor, which directly tells how effective a laser is at suppressing microbunching instability.[6]

However, qualitatively, the double horn distribution essentially acts like two separate cold beams (as seen in blue below) rather than a consistent and even Gaussian spread (as seen in red) that would more effectively induce the rapid energy modulation that would lead to successful MBI suppression.

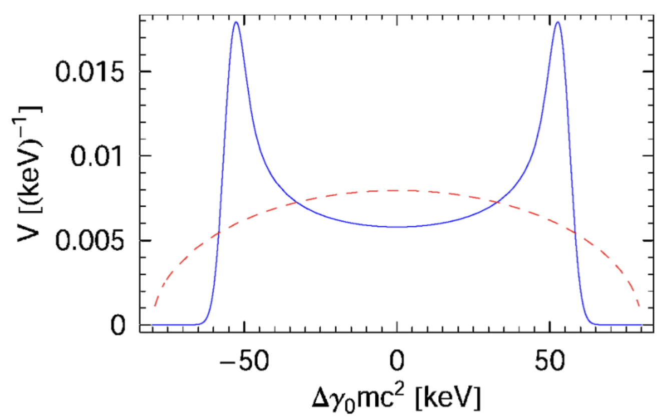

Figure 1. Visual representation of the double horn distribution with horns at ±50 keV that act like separate cold beams.[5]

RESULTS AND INTERPRETATION

According to the paper, for the LG_{01} mode, even with increases of relative energy, the curve was always Gaussian, with the Gaussian merely getting wider and less precise. For the Gaussian mode on the other hand, increases in relative energy actually yielded a double horn structure, which is far less effective in MBI suppression than the LG_{01} mode, even with a poorer Gaussian at high relative energy.

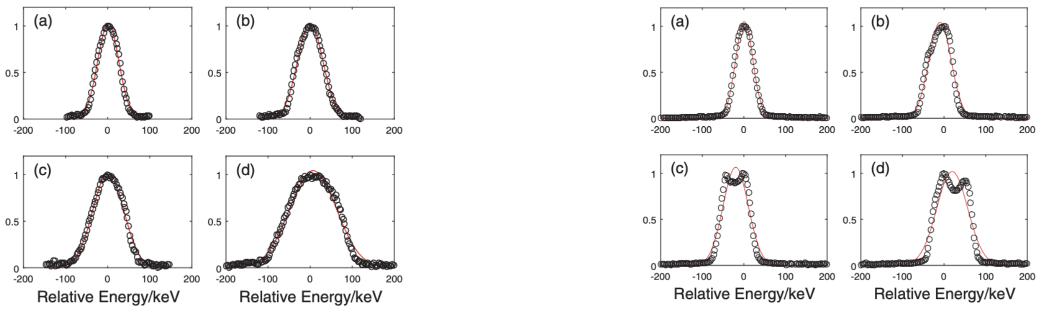

Figure 2. The graphs on the left are the LG_{01} mode; you can see a Gaussian curve at various levels of relative energy. The graphs on the right are the Gaussian mode that have a Gaussian fit, but double horns at 20 - 30 keV.[1]

For the results given by the MIR spectrometer, in the 15 - 20 keV energy spread, the LG_{01} mode has a lower spectral signal contribution as compared to the Gaussian mode, which is an indication that the MBI suppression is more effective.[1]

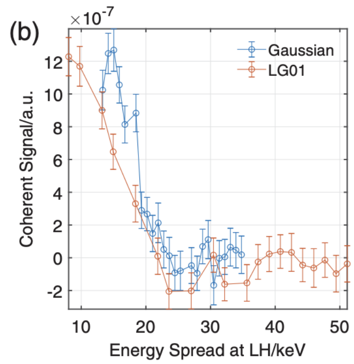

Figure 3. MIR spectral intensity is plotted against the energy spread for Gaussian and LG_{01}[1]

To further analyze the results given by the paper surrounding the double horn distribution, I completed an additional calculation to compare the laser heater used in this paper to a laser heater used in a different paper. The intent of this calculation was to verify that the double horn distribution was not a phenomenon unique to the specific Gaussian laser heater that was used in the original paper, and upon confirming that the two unique Gaussian laser heaters could yield the same double horn spread, I qualitatively analyzed why the double horn distribution was not effectively suppressing microbunching instability, ultimately affirming the paper's original conclusion that the LG_{01} mode laser heater is the superior laser mode for MBI suppression in FELs.

CONCLUSION

Overall, this paper analyzes the use of Gaussian and Laguerre-gaussian laser heaters and their respective effectiveness in suppressing microbunching instability. Although the paper did not quantitatively measure and compare the performance of the two modes, it has come to the conclusion that Laguerre-Gaussian laser heaters are preferable for MBI suppression over their Gaussian counterpart. In the future, more quantitative analysis can be done to verify the conclusion that was presented in this paper.

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