UCLA
Recent Work

Title

Optimizing Laser Heater Profiles: A Review of LG_{01}, Hermite-Gaussian, and Beamlet Array Modes

Permalink
https://escholarship.org/uc/item/3nx0k2jz

Author
Tsai, Matthew

Publication Date
2025-12-11

eScholarship.org
Powered by the California Digital Library
University of California

Optimizing Laser Heater Profiles: A Review of LG_{01}, Hermite-Gaussian, and Beamlet Array Modes

Matthew Tsai,[1*]

[1]*Electrical and Computer Engineering Department, University of California, Los Angeles*

**matthewtsai@ucla.edu*

Abstract: LG_{01} mode laser heaters preserve a Gaussian-shaped energy distribution to suppress MBI and improve FEL. This review investigates alternative shaped intensity beams, including LG_{01}, Hermite-Gaussian, and Gaussian Beamlet Array modes, to prevent transverse laser jitter.

INTRODUCTION

Free-electron lasers (FELs) are an increasingly powerful tool in physics research, allowing scientists to "see" individual atoms at the angstrom level. They are used as atomic-scale "movie cameras," powering detailed atomic research in fields such as drug development, chemistry, and material science. Researchers are able to see atomic interactions in real-time [1], including chemical-bond breaking, unraveling biological macromolecules for advanced drug discovery, and probe the properties of novel superconductors [2,3]. FELs are capable of ultrafast pulses in the femtosecond range, and produce spatially coherent light. It is generated via magnetic compression along an accelerator, which often degrades the electron-beam (e-beam) quality due to microbunching instability (MBI). Small modulations in the e-beam energy and density increase energy spread to a detrimental level [4].

The current method of counteracting MBI, FEL facilities often employ a laser heater (LH), increasing the e-beam's uncorrelated energy spread by a small and controlled amount. This Landau damping suppresses downstream MBI accumulation. Changing the laser heater's pulse allows for direct control over the energy spread and distribution of the e-beam. The traditional method involves a transverse Gaussian-shaped laser beam. However, when the laser spot size is larger than the e-beam to mitigate transverse jitter, it results in a "double-horn" distribution. This can be seen as two separate unheated cold beams. In 2020, Tang et al., discovered that a transverse Laguerre-Gaussian 01 (LG_{01}) mode results in a Gaussian-shaped energy distribution, suppressing MBI. The experiment used a spiral phase plate, which writes an increasing spiral phase onto the beam to generate a characteristic LG_{01} mode, featuring a "null in the field amplitude at the center." The e-beam is aligned to the donut hole of the central intensity null where the linear electric field gradient maps the e-beam's Gaussian transverse profile to a Gaussian energy spread. Unfortunately, experimental results highlighted a negative transverse jitter effect. Noise in the FEL facility can cause pointing and transverse offset jitter in LH, causing the e-beam to occasionally overlap with the maximum intensity of the ring, causing a double-horned energy distribution. This review investigates alternative beam geometry to balance jitter while suppressing MBI. Specifically, LG_{01}, Hermite-Gaussian, and Gaussian Beamlet Array modes will be compared to find an ideal beam shape.

METHODS

To find an ideal beam shape, the susceptibility of each candidate to MBI and jitter must be analytically and/or empirically determined. Microbunching instability is best suppressed by Landau damping, which requires a smooth, Gaussian energy spread distribution in the electron beam. The gain suppression factor for Landau damping (1) depends on the Fourier transform of the electron beam's energy spread distribution

$$S(k) = \int_{-\infty}^{\infty} f(\delta) e^{(-jkR_{56}\delta/\gamma)} d\delta \qquad (1)$$

For the LG_{01} mode, Tang et al., (2020) used the setup in Figure 1 with a LG_{01} mode laser and spiral phase plate to generate a "null in the field amplitude at the center of the laser" [5]. The spiral phase plate is seen in Figure 1, inset 1 and is critical to the central point null of the beam.

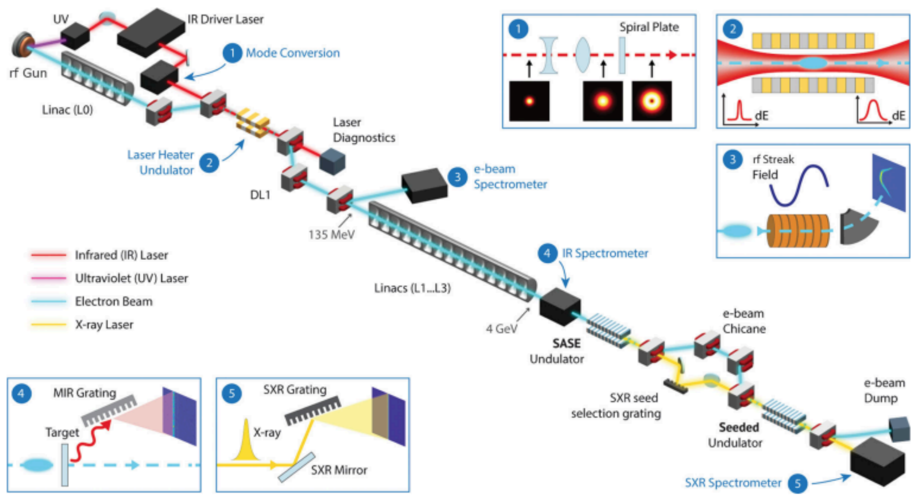

Figure 1: Schematic of experimental setup in Tang et al., (2020), including spiral phase place (inset 1). (Ref. [1], Fig 1)

To quantify the quality of the heating, the shape of the induced energy spread can be compared with the ideal Gaussian distribution using the Gaussian Fit Coefficient (R^2). Lastly, the jitter sensitivity must be compared.

While the LG_{01} and HG_{01} modes are both Gaussian functions, the Gaussian Beamlet Array is defined as a superposition of N individual Gaussian beamlets with grid spacing d (Equation 2). The Beamlet Array relies on statistical sampling. The electron beam size is larger than the individual beamlet spacing, and the electrons sample a wide distribution of laser intensities.

$$I(x, y) = \sum_{i,j} I_0 * \exp - \frac{2(x-id)^2+(y-jd)^2}{w_b^2} \qquad (2)$$

RESULTS AND INTERPRETATION

For the LG_{01} mode, it consistently generates a Gaussian energy distribution with an R^2 value consistently exceeding the traditional Gaussian mode. When the Gaussian energy distribution is substituted into Formula 1, the Fourier transform of a Gaussian function yields another Gaussian function (3). With the exponential decay providing strong damping across the wide spectrum of high-frequency MBIs, and the lack of the double-horned energy distribution of the traditional Gaussian mode, the LG_{01} provides significantly better MBI suppression compared to the traditional Gaussian mode. This was experimentally demonstrated by Tang et al., (2020), whose resulting Gaussian distribution energy spread can be found in Figure 1.

$$S_{LG}(k) = \exp\left(-\tfrac{1}{2}k^2 R_{56}^2 \sigma_\delta^2\right) \qquad (3)$$

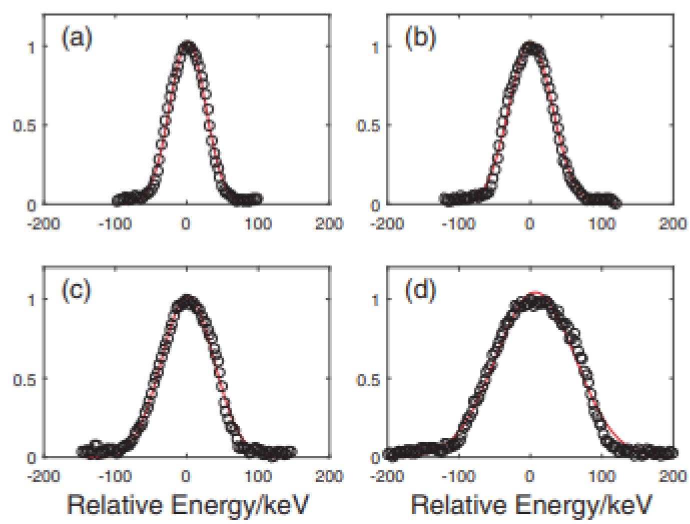

Fig 1: Gaussian energy distribution (a) 25.1, (b) 30.3, (c) 36.8, and (d) 55.7 keV rms energy spread. (Ref. [5], Fig 2)

However, this mode is extremely sensitive to jitter due to its point null at (0,0) in the center of the donut. If the transverse jitter shifts the electron beam, it may overlap with the surrounding donut, resulting in a flat slope of the electric field at E_{max}. As seen in Equation 4, the probability distribution of a sinusoidal energy modulation resulting from a constant field amplitude has 2 sharp double-horn peaks, allowing MBI to persist at small transverse jitter conditions.

$$P(E) \propto \frac{1}{\sqrt{E_{max}^2 - E^2}} \qquad (4)$$

For the Hermite-Gaussian (HG_{01}) mode, the Landau damping is identical to the LG_{01} Landau damping in Equation 3. However, the HG_{01} mode has a line null along the y-axis [6]. If the electron beam jitters along the line null, it remains in the linear electric field region. It therefore retains the ideal Gaussian energy distribution of Figure 2 while being less susceptible to jitter effects.

Lastly, the Beamlet Array has a Landau damping suppression factor in the form of a 2 sided exponential (Equation 5). The damping is not as strong as the LG_{01} or the HG_{01} modes.

$$S(k) \propto \exp\left(-|k| * R_{56} * \Gamma_{eff}\right) \qquad (5)$$

The resulting energy distribution converges to a Lorentzian distribution for a sufficiently dense array (Equation 6). The distribution still has a single peak and long tails, which can provide effective Landau damping without the double-horn (Figure 3).

$$P(E) \propto \frac{1}{E^2 + \Gamma^2} \qquad (6)$$

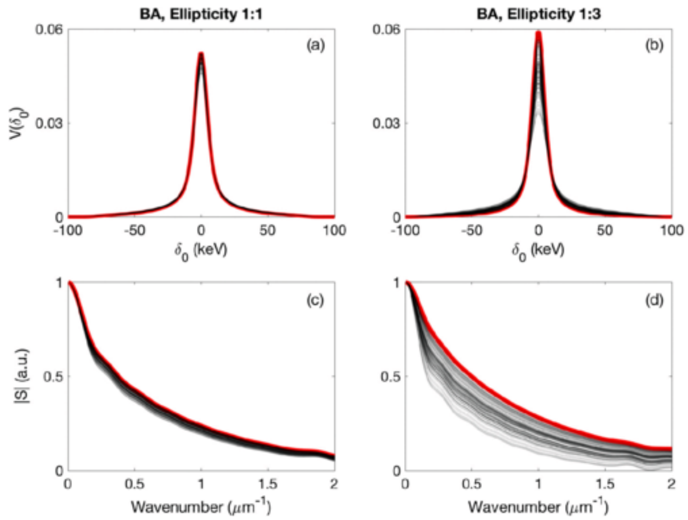

Figure 3: Lorentzian energy distribution for Beamlet Array (Ref. [7], Fig 7)

Jitter moves electrons from one identical beamlet to another, providing excellent jitter stability. However, it was experimentally determined that optimizing the laser for a Lorentzian distribution resulted in a lower MBI suppression [7].

CONCLUSIONS

In conclusion, it is determined that the choice of the best laser mode depends on the user's requirements. There is a balance between the MBI suppression and jitter explored in Table 1.

	Energy PDF	**Jitter Susceptibility**
LG_{01}	Gaussian (ideal)	High (point null)
HG_{01}	Gaussian (ideal)	Medium (line null)
Beamlet Array	Lorentzian	None (spatial averaging)

Table 1: Tradeoffs of LG_{01}, HG_{01}, and Beamlet Array

There are many complex nuances between the different modes that must be considered when choosing a laser mode, including the necessity for high MBI suppression or the susceptibility of specific facilities to jitter. Further research could be done on the optimizations to specific laser modes or on additional laser modes. In addition, further comparisons could be made between the different modes using further data points.

REFERENCES

1. Bostedt, C., et al. "Linac Coherent Light Source: The first five years." *Reviews of Modern Physics* 88.1 (2016): 015007.
2. Chapman, H. N., et al. "Femtosecond X-ray protein nanocrystallography." *Nature* 470.7332 (2011): 73-77.
3. McNeil, B. W., & Thompson, N. R. "X-ray free-electron lasers." *Nature Photonics* 4.12 (2010): 814-821.
4. Huang, Z., et al. "Suppression of microbunching instability in the Linac Coherent Light Source." *Physical Review Special Topics-Accelerators and Beams* 7.7 (2004): 074401.

5. J. Tang, et al. "Laguerre-gaussian mode laser heater for microbunching instability suppression in free-electron lasers." Physical review letters **124**(13) (2020): 134801.
6. V. Fann, "Hermite-Gaussian Mode Laser as an Alternative to the Laguerre-Gaussian Mode for Microbunching Suppression," eScholarship (2023).
7. Liebster et al., "Laguerre-Gaussian and beamlet array as second generation laser heater profiles.: Phys. Rev. Accel. Beams 21 (2018): 090701