Title

Cracking the Code: Laguerre-Gaussian Modes and the Battle Against Microbunching Instability

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Cracking the Code: Laguerre-Gaussian Modes and the Battle Against Microbunching Instability

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Abstract: A collective phenomenon that is observed with FELs due to the high density of electrons is intensity instability. The particles create sizable fields that work back onto the beam itself which can change the longitudinal phase distribution. This phenomenon is known as microbunching instability (MBI). Techniques have been developed to mitigate this phenomenon with decent efficiency. We look to validate the technique used in the research article [1] by comparing it to the standard model [6] while giving some background on the factors that add to the instability.

I. INTRODUCTION:

Microbunching instability (MBI), commonly observed in free-electron lasers (FELs), is driven by synchrotron radiation (CSR), a well-known phenomenon. This radiation arises from the bending of electrons' paths of travel as they are forced through a region with periodically varying magnetic fields [5]. This region within the FEL is known as the "wiggler" [3]. The resulting radiation has a characteristic polarization and spans a broad portion of the electromagnetic spectrum, which becomes superimposed on the desired laser emission. This leads to a significantly broader spectrum than expected for a fine-bandwidth laser [6].

However, the wiggler is crucial because it counteracts another contributor to MBI: the bunching of electrons, which creates incoherent, or modulating, density and energy distributions. The wiggler acts as a smoothing mechanism, smearing out these distributions and enhancing the coherence of the beam.

Unfortunately, this trade-off is unavoidable. The magnetic field is essential to slow down the electrons and facilitate their interaction with the atoms in the material. This interaction promotes lasing through stimulated emission, or amplification, by increasing the probability of electrons stimulating atoms [2].

These are highly researched topics, and researchers have developed various methods to effectively balance and control these contributors to instability. One such approach explored in the research article [1] utilizes an LH cavity, wiggler, and a spiral phase plate in concert to generate a doughnut-shaped beam (Laguerre-Gaussian mode LG01). This configuration preserves the desired low-bandwidth Gaussian distribution of the laser emission.

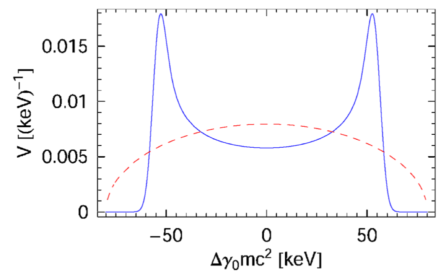
In this review paper, we analyze the technique of using LG01 modes and their impact on the levels of CSR and modulation. By comparing these findings with the standard MBI suppression technique presented in [6], we gain a deeper understanding and appreciation for the use of both methods.

II. Methods:

Traditionally, the use of laser heaters produces a standard Hermite-Gaussian distribution, which, in theory, when aligned with the spot size of the electron beam, should restrict the electron beam from experiencing exponential growth in density and energy modulations, thereby preserving the output quality of the FEL. This method has been demonstrated in simulations, as highlighted in [6]. In that study, simulations were carried out using an LH with both a significantly larger spot size and a spot size matched to the electron beam. The outcome is illustrated in the energy distribution graph produced by their simulation. I show them below for reference.

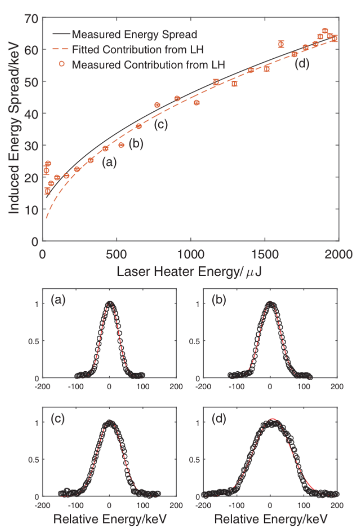
Main parameters for the LCLS laser heater.

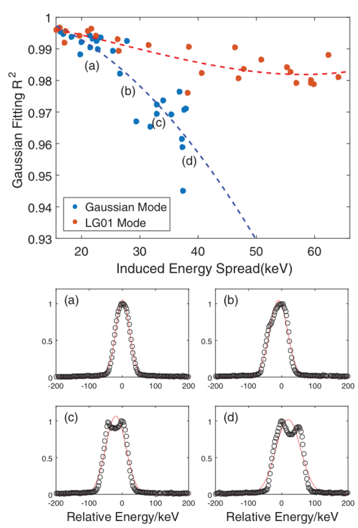
Parameter	Symbol	Value
Electron energy	$\gamma_0 mc^2$	135 MeV
Average beta function	$\beta_{x,y}$	10 m
Transverse rms e-beam size	$\sigma_{x,y}$	190 μm
Undulator period	λ_u	0.05 m
Undulator field	B	0.33 T
Undulator parameter	K	1.56
Undulator length	L_u	0.5 m
Laser wavelength	λ_L	800 nm
Laser rms spot size	σ_r	175 μm (1.5 mm)
Laser peak power	P_L	1.2 MW (37 MW)
Rayleigh range	Z_R	0.5 m (35 m)
Maximum energy modulation	$\Delta\gamma_L(0)mc^2$	80 keV (55 keV)
rms heater-induced local energy spread	$\sigma_{\gamma_L} mc^2$	40 keV



(Color) Electron energy distribution after the laser heater for a large laser spot (blue solid curve) and for a matched laser spot (red dashed curve).

In the research article [1], it was demonstrated that by using a spiral phase plate (SPP) [1,4], the standard Hermite-Gaussian beam can be transformed into a Laguerre-Gaussian beam (LG01). This makes the beam take the form of a ring which the electron beam is concentric to. The resulting distributions from using an LG01 beam to mitigate modulations is show below.





III. RESULTS AND INTERPRETATION

Note that the LCLS laser heater is used in both of these experiments for its relevance and effectiveness with FELs. This is beneficial because both experiments use the same LH parameters which makes the comparison much easier. If different LHs were used, we would need to consider the impacts of the LH parameters themselves.

For the simulations done in [6] the graph for energy distribution, $\Delta\gamma_0 mc^2$, for a larger spot size (blue) produces the dreaded double horn distribution. Whereas if the LH spot size is matched (red) we maintain a Gaussian-like distribution. These were idealized simulations where initial modulations could be disregarded since their contribution to the overall modulations were minimal. The main issue with these idealizations is that in real-life applications we must account for the jitter that is common with high density electron beams. Because of this jitter we could never make the spots size exactly equal to that of the electron beam. Thus the result in practice is the double horn distribution. This means that using only a standard Gaussian heater has trouble mitigating the effects of both the synchrotron radiation (CSR) and longitudinal space charge (LSC) modulations.

For the simulation done in [1], it was shown that more power would be needed to cause the beam to experience similar spread as in [6]. However, it was also found that the beam can far exceed the spreading capabilities of the standard model in [6]. The LG01 setup could reach 65keV of energy spread where MBI suppression usually occurs around 20-30keV. Thus, the LG01 method is more capable of spreading the beams energy. This is significant because it results in the preservation of the energy spread over several stages of compression. In addition, we should consider the contribution of CSR in each case. The equation to determine the power emitted by a single electron inside of a magnetic field where the electrons are moving in a circular path is [7]:

$$P_{CSR} = \frac{2Ke^2\gamma^4v^4}{3c^3r^2}$$

Where (K) is the undulator parameter, (γ) I the Lorentz factor, (r) is the rms electron beam size, and (c) is the speed of light. Converting the equation and all the relevant parameters into code [8], I found that the amounts of power produced can be calculated per electron. This value is proportional to the total CSR produced by the beam. The values are:

Synchrotron radiation power per electron for Hermite-Gauss LCLS: 2.4042461889l9493e-06 W
Synchrotron radiation power per electron for Laguerre-Gauss LCLS: 3.471731496799748e-05 W

This shows that on average, the electrons with the LG01 mode from the LCLS are an order less in magnitude than that of the standard Gaussian LCLS. Thus, the CSR contribution for the LG01 was much less leading to better controllability and thus a higher quality laser.

To figure out the total contribution of gain from CSR to the output distribution, the CSR gain factor would need to be calculated [9]. The CSR gain factor is a measure of how effectively CSR amplifies the initial density modulations. It can be expressed as:

G(ω) = |∫ F_s(z, z', ω) exp(-ik(z - z')) dz'|^2

Where (ω) is the angular frequency, (k) is the wavenumber, and (F_s) is the electric field. If calculated, we would see that the gain factor would be less in [1] as opposed to that in [6].

IV. CONCLUSIONS

The use of the LG01 method showcased in the research article under review [1], is more effective and practical at suppressing MBI as opposed to the traditional theoretical approach outlined in [6]. Although it requires a more complex setup, with a spiralizer and increased power from the LH itself, it greatly outpaces the older approach. This is a step in the right direction for developing systems and techniques for creating high quality lasers.

V. References

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