Title

Microbunching Instability Suppression using Laguerre-Gaussians and Transverse Laser Size

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Microbunching Instability Suppression using Laguerre-Gaussians and Transverse Laser Size

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Abstract: High brightness and high intensity free electron lasers (FELs) have become indispensable tools for researchers exploring interactions at the smallest scales. However, their inherent brightness and intensity give rise to microbunching instability, compromising the coherency of the electron beam (e-beam). Laguerre-Gaussian laser heaters have demonstrated superiority over conventional Gaussian laser heaters in suppressing microbunching instability, although at the expense of higher energy requirements. Increasing transverse laser size is shown to not assist in ameliorating transverse jitter effects.

INTRODUCTION

Gaussian mode laser heaters (LH) have proven useful in recent years at the Linac Coherent Light Source (LCLS) in the suppression of microbunching instability (MBI) that leads to uncontrolled gain and degrades the quality of the e-beam in the free-electron lasers (FEL) employed at the LCLS, which operate at high brightness and current [1]. Gaussian LH'S have been the primary tool in suppressing MBI, but more recently the Laguerre-Gaussian 01 mode (LG_{01}) has been shown to be more effective in MBI suppression [1]. This comes at the cost of a power consumption at least an order of magnitude greater than that of Gaussian LH's, but this higher power consumption comes with a lower final energy spread than is currently achievable with traditional Gaussian LH's. While all FEL LH's are susceptible to undesirable transverse jitter effects, LG_{01} LH's are particularly sensitive to them, though there are multiple approaches that could be mitigate their effect on the final slice energy spread [1]. The development of MBI-suppressing LH's promises to facilitate advancements in many scientific fields such as material science, chemistry, biology and condensed matter physics [2], as FEL's become an increasingly important tool to scientific researchers, and so their study holds tangible benefits to society at large.

METHODS

Microbunching instability at FEL facilities is generally countered by the use of a LH, which is a short undulator coupled with an infrared (IR) laser that copropagates with the e-beam. In a Gaussian LH, the transverse beam size of the laser is ~1.4-2 times that of the e-beam, which modulates and increases the energy spread of the e-beam, thus preventing uncontrolled energy spread further down the linac, effectively dampening MBI, and can increase the brightness of the e-beam by a factor of 3. The letter under discussion here experimentally analyzes the efficacy of the LG_{01} mode LH, which is shown to induce a more Gaussian shaped energy distribution. A Gaussian final energy profile is desired as it indicates better suppression of MBI via Landau damping [2]. It is shown thus the LG_{01}suppresses final microbunching gain better than the regular Gaussian LH.

One of the main benefits of the LG_{01} mode LH is that it is not required to transversely overlap the e-beam to induce an energy spread, as with the Gaussian LH. Rather, the e-beam propagates in the intensity minimum region located in the center of the donut-like transverse profile unique to certain Laguerre-Gaussian modes. This results in an e-beam that experiences a linear electric field and conveniently maps the Gaussian transverse distribution of the e-beam to its longitudinal plane [1]. As a result, the LG_{01} mode LH results in an e-beam that is generally less susceptible to the double-horn pattern at higher induced energy spreads. The 2018 letter shows how the double-horn pattern is first noticeable at around 26.7 keV induced spread and very apparent at 30.1 keV, an undesirable effect as this occurs in a range that is considered optimal LCLS operating conditions. The LG_{01} mode LH on the other hand, continues to induce a Gaussian energy profile of the e-beam up to induced energy spread of 55.7 keV. These profiles are characterized with the aid of the first diagnostic mentioned, a 135 MeV spectrometer, which are extracted from the central time slice of the e-beam [1].

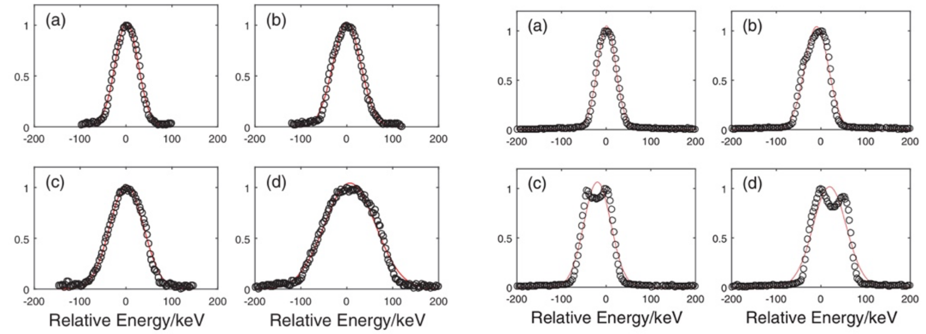

Fig. 1. Final slice energy spread for the LG_{01} LH on the left and the Gaussian on the right. Measured at 135 MeV. LG_{01} measurements taken at a) 25.1, b) 30.3, c) 36.8, d) 55.7 keV rms induced energy spread. Gaussian measurements taken at a) 20.5, b) 26.7, c) 30.1, d) 37.2 keV rms induced energy spread. Figure from Tang 2020 (Ref. [1] , Fig. 3).

The 2018 letter mentions a second diagnostic, in the form of a midinfrared (MIR) spectrometer downstream of the linac when the e-beam reaches an energy of 4GeV. This characterizes MBI and MBI suppression by taking the Fourier transform of the longitudinal e-beam distribution and noting that lower MIR frequency components correspond to the coherent e-beam, while higher frequency components represent MBI. The 2018 letter compares the integrated MIR spectral intensity for the LG_{01} mode LH and the Gaussian LH and notes better MBI suppression for the LG_{01} mode LH, particularly in the 15 to 20 kEV range, than that of the Gaussian LH [1].

Increased monochromaticity is another indicator of MBI suppression and it is indeed shown to be improved by 20% within 1 eV in the soft x-ray self-seeding (SXRSS) spectrum over a single-beam Gaussian LH, which would be useful in seeding even more powerful lasers. The higher power demands of the LG_{01} mode LH are the trade-off for achieving an ultimately lower final slice energy spread (SES). Figure (2) shows minimum SES of the LG_{01} mode LH due to MBI to be approximately 300% lower than the minimum possible SES of the Gaussian LH. This increased capability of MBI suppression occurs in the range ~9-25 keV, a wider and more convenient range of induced spread for the LCLS.

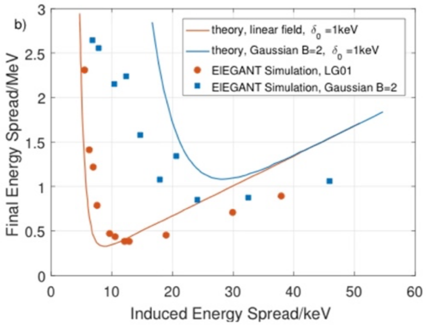

Fig. 2. Final energy spread at the end of linac as a function of induced energy spread at laser heater by theory [4] and ELEGANT simulation (squares and circles) of the two modes. Figure from Tang 2020 supplement (Ref. [1] supp., Fig. 3).

Transverse jitter effects arise from a misalignment of the e-beam center in relation to the center of the LH beam. Undesired e-beam overlap can lead to a non-Gaussian final SES, compromising MBI suppression. While both Gaussian and LG_{01} mode LH's are susceptible to transverse jitter, Gaussian LH's are more susceptible as jitter can induce a pedestal pattern around a central energy peak, and this is compounded when incorporating e-beam ellipticity, as these conditions most closely resemble routine operations at the LCLS [2]. With this it becomes impossible to generate Gaussian-like e-beams with the Gaussian LH. LG_{01} LH's are more resilient to jitter and ellipticity, as their larger size means jitter effects occur more infrequently, excessive jitter can induce a slight double-horn distribution. This could be remedied by stabilizing the LG LH using a waveguide.

RESULTS AND INTERPRETATION

Intensity distribution is defined for a Gaussian LH as

$$h(r) = A \cdot e^{-r^2/2\sigma_r^2}$$

where A is the normalization constant

$$A = \sqrt{2 \cdot (1 + \frac{1}{B_G^2})} \cdot \sigma_\delta$$

and for the LG_{01} LH as

$$h(r) = A \cdot r \cdot e^{-r^2/2\sigma_r^2}$$

where the normalization constant is

$$A = (1 + \frac{2}{B_{LG}^2}) \cdot \sigma_\delta$$

And $B = \sigma_r/\sigma_x$. Here σ_δ is the energy spread at the undulator, σ_r is the transverse laser heater size and σ_x is the transverse e-beam size. It has been found that for a LG LH a ratio of B ≥ 5 simulations of final SES approach a mathematically perfect Gaussian distribution, but no upper limit is given. Figure (3a) shows how MBI suppression remains constant for larger B_{LG} ratios [3]. Figure (3b) shows that increasing σ_r, and thus B_{LG} ratio, does not widen the central lower intensity region of a LG_{01} LH, and thus would not be useful in ameliorating transverse jitter effects. If offset jitter could be stabilized below 80 µm, either through a LH waveguide in conjunction with apertures and beam stabilizers for the e-beam, even more consistent and stable heating could be achieved and the worse effects of transverse jitter would be avoided [2].

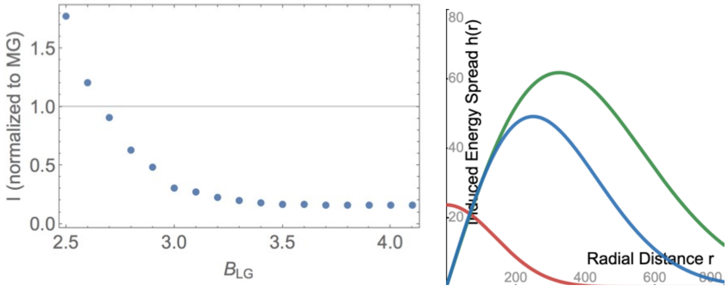

Fig. 3(a) and (b). On the left (a), LG laser profile suppression integral as a function of B_{LG}. Figure from Proceedings of FEL 2015 (Ref. [3], Fig. 2). On the right (b), induced energy spread as a function of r in µm. Red is h(r) for a Gaussian LH, blue is a LG_{01}LH with σ_r= 325µm and green is a LG_{01}LH with σ_r= 500µm.

CONCLUSIONS

It has been shown that Laguerre-Gaussian laser heaters outperform Gaussian laser heaters in terms of lower possible final energy spread as well as resiliency to e-beam ellipticity. Higher order LG modes do not seem to be a viable option to resist transverse jitter effects and so this should be pursued by propagating the LG LH beam with waveguides and e-beams with apertures and beam stabilizers.

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