Title

Review Paper: Laguerre-Gaussian Mode Laser Heater for Microbunching Instability Suppression in Free-Electron Lasers

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Review Paper: Laguerre-Gaussian Mode Laser Heater for Microbunching Instability Suppression in Free-Electron Lasers [1]

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Abstract: Free Electron Lasers (FELs) capabilities are constrained by Microbunching Instability (MBIs) that occurs in the Electron Beam. A Laguerre-Gaussian (LG01) mode Laser Heater (LH) suppresses MBI better than the current standard, a Gaussian mode LH.

INTRODUCTION

Free Electron Lasers (FELs) are employed within the medical field, materials science, and in this case, imaging of physical processes, specifically, at the Linac Coherent Light Source (LCLS) facility. Utilizing linear accelerators, electron beams, and chicanes, FELs produce monochromatic X-ray emission within an undulator. Unfortunately, their quality as a spectrometer is reduced by Microbunching Instability (MBI) effects. MBI is caused by longitudinal space charges as well as synchrotron radiation within the laser, which leads to instability that reduces beam brightness, monochromaticity, and other qualities of the FEL. For this reason, Laser Heaters (LH) are implemented within the FEL to suppress MBI by improving the energy spread of the electron beam that is propagated longitudinally. Previously the LH used at the LCLS facility was a Gaussian mode LH. The paper proposes a Laguerre-Gaussian 01 (LG01) mode LH as an option, due to its unique ring-shaped transverse intensity distribution [2]. Additional state-of-the-art include Laser Plasma Accelerators (LPAs) which remove the Linacs that add to MBI, leading to improved qualities [3].

METHODS

The primary objectives of the experiment are to verify an improved MBI suppression from the LG01 mode and compare them to the Gaussian mode. The process of quantifying the performance of a LH follows a measurement process defined by the FEL layout in the LCLS facility (Fig. 1). To begin, a spiral phase plate (SPP) is used to alter the original Gaussian mode LH into an LG01 mode by a change in phase of 2π. This is possible because both LHs are Laguerre-Gaussian Transverse Electric-Magnetic waves that propagate in unique modes which determine their intensity distribution (Eq. 1) [4]. The SPP enables 95% transmission efficiency which is sufficient to induce energy spread at the optimal and higher levels. Verification of improved induced energy spread is done with a 135MeV spectrometer placed past the LH which takes a central time slice of the electron beam up to 65keV. The final results are evaluated by their likeness to an ideal gaussian shape.

The second indicator of performance is a Mid Infrared (MIR) spectrometer placed past the point where the e beam reaches 4GeV, the final energy. Through secondary emission of the e beam radiation in self-amplified spontaneous emission (SASE), MBI suppression can be determined since radiation is proportional to the MBI factor. Simulation in ELEGANT provides monochromaticity measurements with the LG01 mode LH. Finally, the effect of transverse jitter is quantified by online cameras and tracking of the LH to find an optimal center and the induced error.

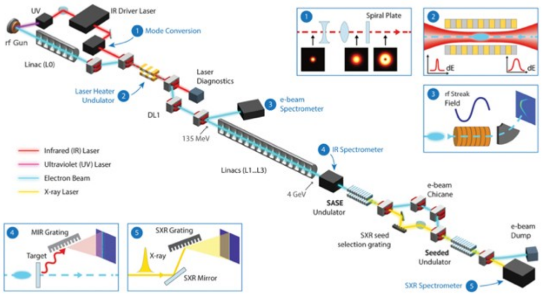

FIG. 1. Simplified schematic of start-to-end experimental configuration, from the photoinjector to the SXRSS diagnostic end station (not drawn to scale).

$$\begin{aligned}\hat{\mathcal{E}}_{mn}(x,y,z) &= \frac{C_{mn}}{w(z)} H_m\left[\frac{\sqrt{2}x}{w(z)}\right] H_n\left[\frac{\sqrt{2}y}{w(z)}\right]\exp\left[\mathrm{i}\frac{k}{2}\frac{x^2+y^2}{q(z)}\right]\exp\left[\mathrm{i}\zeta_{mn}(z)\right] \\ &= \frac{C_{mn}}{w(z)} H_m\left[\frac{\sqrt{2}x}{w(z)}\right] H_n\left[\frac{\sqrt{2}y}{w(z)}\right]\exp\left[-\frac{x^2+y^2}{w^2(z)}\right]\exp\left[\mathrm{i}\frac{k}{2}\frac{x^2+y^2}{\mathcal{R}(z)}\right]\exp\left[\mathrm{i}\zeta_{mn}(z)\right]\end{aligned} \tag{1}$$

RESULTS AND INTERPRETATION

The principle result of the experiment confirms that the Laguerre-Gaussian 01 mode LH is better suited to reduce Microbunching Instability than a Gaussian mode Laser Heater. This was made evident by comparison of the Gaussian fitting R^2 factor of both lasers across the induced energy spread of 15keV to 65keV. Despite initial values of the factor begin similar, by the 30keV region there is a large disparity, with the LG01 mode factor being more favorable. This disparity aligns with the appearance of the double horn structure in the energy distribution which is shown to be apparent when comparing the energy spread across only a single laser energy. Although the Gaussian mode similarly traced a Gaussian curve for low laser energies, this may be a false conclusion since it is greatly dependent on the accuracy of the spectrograph at low energies. The secondary result comes from the SASE spectrometer which are plotted onto a spectrograph showing that for the 15 to 20 keV range the LG01 mode has a lower spectral intensity than the Gaussian mode. Both of these analyses found the aforementioned results to be correct.

In addition to the direct evidence of reduction in MBI, the Laguerre-Gaussian 01 mode LH also improved monochromaticity. The analysis performed through a theoretical simulation in ELEGANT found a 20% improvement in the monochromaticity of the soft x-ray self-seeded (SXRSS) FEL emission. Despite the goal of the paper being the comparison of the two modes, for this measurement it was not possible to compare their effects on monochromaticity. Monochromaticity requires a single wavelength as opposed to a spectrum of wavelengths and is highly desired to producent coherent emission [4].

An additional attribute of the laser in this analysis is the noise produced by the Transverse Jitter Effects which was solved by creating the Gaussian Mode spot several times larger than the e beam. Transverse Jitter Effects impact the Laguerre-Gaussian 01 mode greatly in a detrimental way due to the intensity distribution. This effect is caused by noise in both the acoustic and thermal categories, which compromises the laser heater and electron beam. Specifically, Transverse Jitter Effect cause them to overlap shot to shot in high energy modes making the electron beam intensity overlap the LG01 mode in a negative way. This is quantified by the Gaussian fitting R^2 factor for different rms changes in positioning from the optimum pointing direction.

CONCLUSIONS

To sum up, the effects of Microbunching Instability within FELs is created by the electron beams and the space charge density within the lasers longitudinal plane, but it can be mitigated by the use of laser heaters. The paper furthered the field by proving the improved effectiveness of a Laguerre-Gaussian 01 mode LH over the standard Gaussian Mode laser heater. Additional recent work in the field has found that transverse-to-longitudinal phase space mixing and large slice energy spread of the electron beam can also efficiently improve the Microbunching Instability suppression for FELs [5].

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