Title

Advancements in Microbunching Instability Suppression: Theoretical Implementation of Speckle Array Laser Heater in Free Electron Lasers

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Publication Date

2023-12-11

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Abstract:

Addressing Free-Electron Laser limitations, this study investigates the theoretical feasibility of a speckle array laser heater to mitigate microbunching instability (MBI) independently of initial electron distribution, emphasizing wavelength adjustments for optimization.

INTRODUCTION

Free-electron lasers (FELs) are fundamental for scientific research, materials science, medical imaging, industrial applications, energy research, defense, security, and environmental science due to their diverse range of applications and precise capabilities. The process of creating an FEL beam employs electron beams (EBs) with high intensity and current, achieved through magnetic compression of the electron beams along an accelerator [2].

However, FELs suffer from a phenomenon known as microbunching instability (MBI) [3-7] during the compression of EBs, which degrades the quality of the FELs. MBI affects the FEL's quality because it amplifies the EB's energy beyond its tolerance; to a beam degrading point [8,9]. Luckily, MBI can be sufficiently suppressed by incorporating technology that is now integrated into almost all short-wavelength FEL projects: a laser heater (LH).

The heater setup [Fig. 1] largely comprises of a short undulator within a chicane plus a copropagating infrared (IR) laser that modulates and increases the energy spread of the EB while simultaneously remaining below FEL tolerances to maintain beam quality. The energy modulation induces Landau damping and suppresses downstream MBI accumulation, which has been shown to result in a greater FEL intensity by a factor of 3 [3]. The final EB energy distribution is highly dependent on the underlying distribution of induced energy spread [10].

Traditionally, the EB's electrons undergo energy amplification based on their position relative to the laser’s transverse distribution. Therefore, the induced energy spread distribution can be controlled by transversely shaping the LH pulse to match the EB’s profile, facilitating the desirable bell-shaped FEL energy distribution [1].

In the article by Tang et al. (2020), a Laguerre-Gaussian mode laser heater (LHLG$_{01}$) [1] was verified to be effective at MBI suppression and produced the optimal bell-shaped FEL energy distribution. One drawback of this method is the requirement for precise measurement of beam size beam distribution to match it to the EB [11].

Therefore, an approach that yields a bell-shaped energy distribution independent of the electron distribution was studied: the speckle array laser heater (SALH). This technique involves creating a beamlet array of $LHLG_{01}$ modes [Fig. 2] using a spatial modulator which results in the EB experiencing varied modulation amplitudes spatially; ultimately producing a bell-shaped FEL energy distribution [11]. Additional benefits to this technique are its potential to utilize adaptive optics and algorithms to minimize power consumption while also maximizing MBI suppression [10]. However, we cannot achieve this method successfully with the current LH hardware we have because the speckle pattern of SALH must be maintained through the LH undulator; this means the confocal length of the speckle array beams must exceed that of the LH undulator length. This paper will explore a potential theoretical modification to the LH laser operating wavelength that increases the confocal length beyond the LH undulator length along with adding a spatial modulator, to enable the successful implementation of a SALH.

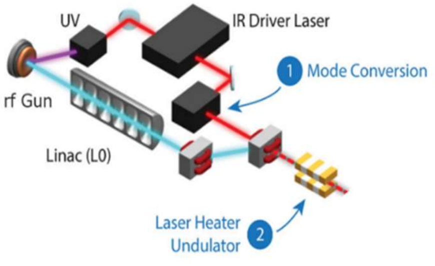

Figure 1: Laser Heater setup [1]

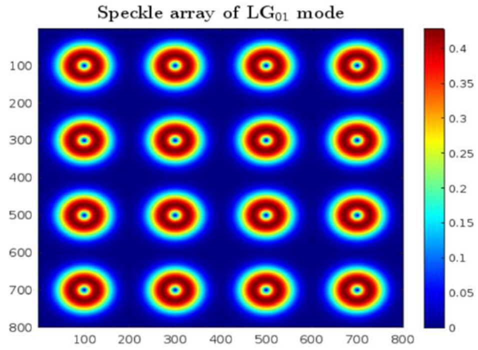

Figure 2: MATLAB generated plot of Example of $LHLG_{01}$ mode speckle array transverse profile

METHODS

In the original paper, the LH setup utilizes a 50 cm long undulator, necessitating the speckle array beams to possess a confocal length greater than 50 cm. The confocal length of the LG_{01} beam is defined by the equation:

$$b = 2\pi w_0^2/\lambda,$$

where w_0 represents the smallest feature of the beam waist, and λ denotes the LH laser's operating wavelength. For an LG_{01} speckle array, the most optimal w_0 is determined to be 100 micrometers for our array with a rms spot size of 200 micrometers and a spacing of 500 micrometers between beams of the speckle array [10], while the IR laser operates at a wavelength of 758 nanometers [3]. This yields a confocal length of approximately 8 cm, which is considerably smaller than the LH undulator's 50 cm length. To ensure b > LH undulator length, the only possible alteration is one made to the laser's wavelength, as modifying w_0 would compromise the optimization of our speckle array.

A MATLAB plot was generated to illustrate the confocal length as a function of UV and IR wavelength lasers [Fig. 3], indicating potential UV lasers that could replace IR lasers in the LH to produce the speckle array. Analysis from Figure 4 reveals that employing any

LH laser in the IR range fails to maintain the required transverse array through the LH undulator, as all plausible values result in a confocal length below 50 cm. Conversely, utilizing any UV laser range to generate the speckle pattern in the LH is suitable, given that part of the UV range covers a confocal length greater than the LH undulator length.

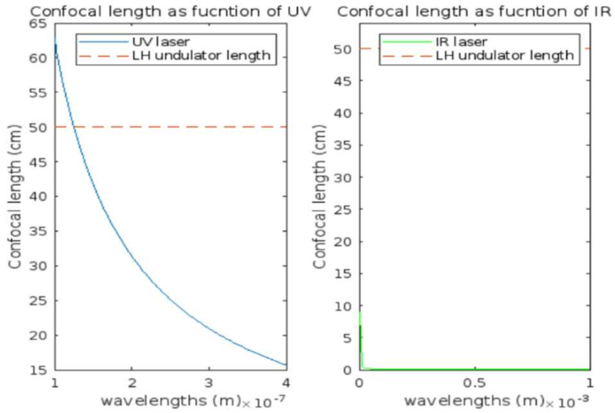

Figure 3: displays the relationship between laser wavelengths and the resulting confocal length of the LG_{01} beams that comprise the speckle array within the LH.

RESULTS AND INTERPRETATION

Implementing a spatial modulator to adjust the laser heater for creating a speckle pattern and substituting the paper's infrared (IR) laser with an ultraviolet (UV) laser within the range of 10^{-7} to 1.27×10^{-7} meters has successfully proven theoretical plausibility in generating a speckle array with a confocal length longer than the LH undulator length. In contrast, attempts to utilize optimal parameters (w_0 = 100 micrometers) with an IR wavelength range were not possible, which resulted in confocal lengths significantly shorter than the LH undulator length. Achieving the implementation of the speckle array LH yields a more power-efficient and beam-matching-insensitive approach relative to the LG_{01}LH.

CONCLUSIONS

This study aimed to assess the theoretical viability of adopting the SALH as an alternative to the LG_{01}LH for initial charge distribution independent MBI suppression in FELs. While the LG_{01}LH showed high potential in MBI suppression, its requirement for precise beam measurements to match the initial EB distribution posed significant challenges due to the need to modulate to precisely produce a final Gaussian energy distribution in the FEL beam.

Consequently, we explored the SALH due to its capacity for MBI suppression irrespective of the initial EB distribution. However, efforts to implement the SALH using the IR laser found in the LG_{01} mode LH led to confocal lengths that were impractically shorter than necessary.

This study identified a promising approach by substituting the IR laser with a UV laser with a range of 10^{-7} to 1.27×10^{-7} meters and incorporating a spatial modulator, showcasing potential in achieving a longer confocal length crucial for compatibility with the original paper's LH undulator. These findings highlight the significance of wavelength selection and beam characteristics in optimizing FEL performance. Lastly, future research considerations may be modifying the LH undulator length rather than focusing solely on altering the confocal length to enhance MBI suppression.

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