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Impact of Laser Wavelength on Microbunching Suppression in FEL Laser Heaters

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Abstract: This review explores how changing laser heater wavelength can improve resonant energy modulation and microbunching suppression, extending results from Laguerre-Gaussian mode laser heater experiments.

INTRODUCTION

Free-electron lasers (FELs) provide coherent, high brightness radiation that has become essential for research in atomic physics, material science, chemistry, and biology. Their performance depends critically on maintaining the quality of the electron beam throughout acceleration. To achieve high peak currents that are required for FEL operation, the electron beam is magnetically compressed along the accelerator [5]. The electron beam has small density and energy modulations that are amplified during magnetic compression, causing microbunching instability. This instability causes an energy spread of the beam, that in turn reduces FEL gain and brightness.

A method of suppressing microbunching instability involves using a laser heater to add a controlled energy spread to the electron beam prior to compression. The interaction between infrared laser and the electron beam inside an undulator causes electrons at different locations to gain slightly different energies. The induced energy spread by the laser heater directly affects how well microbunching is reduced. In the reference experiment by Tang et al., using a Laguerre-Gaussian mode laser heater produced a more Gaussian energy distribution in the electron beam [1].

The wavelength of the laser heater is a fundamental parameter that affects the interaction between the laser heater and the electron beam. It relates to the resonance condition with the undulator, the slippage between the laser and electron beam, and the uniformity of the induced modulation. This review examines the role of heater wavelength, using results from the Laguerre-Gaussian laser heater experiment.

METHODS

The following analysis builds off of the experimental set-up presented by Tang et al., where a 135 MeV electron beam interacts with an infrared laser. In this experiment, a spiral phase plate was used to convert a Gaussian transverse profile into a LG_{01} mode, enabling a comparison of induced energy spread [1].

In order to examine the role that wavelength plays, we will extend the framework that was used in the experiment described. The FEL resonance condition,

$$\lambda_L = \frac{\lambda_u}{2\gamma^2}(1 + \frac{K^2}{2})$$

indicates the optimal heater wavelength for a given undulator strength parameter K, undulator period λ_u, and electron energy γ [2]. When the above condition is satisfied, electrons remain matched in phase to the laser field as they travel through the undulator, maximizing the interaction between the electron beam and the heater.

The wavelength used in the Tang et al. experiment was not explicitly stated but can be calculated based on the above condition and provided values. Using an electron beam energy of 135 MeV, an undulator strength parameter of K=1.56, and an undulator period of 0.05 m, we can approximate the optimal laser heater wavelength to be about 800 nm. This is a reasonable approximation as it is consistent with the parameters of the LCLS laser heater system [3].

Table 1. Laser Heater Parameters Used in Tang et al. Experiment

Parameter	Value
Electron energy at LH	135 MeV
LH undulator strength parameter	1.56
LH undulator length	0.5 m

In addition to resonance matching, the wavelength also affects the slippage between the laser heater and the electron beam. Slippage is proportional to the number of undulator periods and laser wavelength: [4]

$$S \propto N_u \lambda_L$$

Increased slippage can lengthen the interaction between the laser and each electron, thereby smoothing out the induced modulation.

Finally, the magnitude of energy modulation scales with the laser field amplitude and the coupling factor.

$$\Delta\varepsilon \propto E_L F(\lambda_L)$$

The coupling factor $F(\lambda_L)$, is wavelength-dependent and describes how efficiently the laser wavelength drives modulation. A resonant wavelength maximizes the coupling factor of the laser and the electron beam which allows for an induced energy spread to be achieved with minimal power. Off resonant wavelengths reduce the interaction and therefore require more power to obtain the same heating and induced energy spread.

The resonance condition, slippage, and laser field amplitude form our basis for evaluating the wavelength influence on induced energy spread and microbunching suppression.

RESULTS AND INTERPRETATION

Energy modulation of the electron beam depends on how well the laser heater wavelength satisfies the resonance condition. Although the utilized wavelength in the Tang et al. experiment was not specified, the ideal resonant wavelength can be found to be about 800 nm which falls in the wavelength range of a Ti:Sapphire laser operating in the near-infrared region.

The resonant wavelength maximizes the coupling factor, $F(\lambda_L)$, and therefore the modulation amplitude at a fixed laser power. If an off-resonant wavelength is used, the coupling factor decreases, and more laser energy would be required to achieve the same induced energy spread in the electron beam. This reduces the efficiency of the heater and weakens microbunching suppression since the final energy spread is smaller than intended. The suppression of microbunching instability therefore depends not only on the transverse mode of the heater, but also on how well the wavelength satisfies the resonant condition.

Slippage is another wavelength-dependent effect that influences the induced energy spread. Slippage measures the amount of shift between the laser and the electron beam as they propagate through the undulator. As described in the methods section, a longer laser wavelength leads to a larger slippage length. Increased slippage smooths the modulation along the bunch. Smoother modulation can produce a more Gaussian final energy spread, which is desirable for microbunching suppression. This is a similar effect to how the LG_{01} mode in the Tang et al. experiment produced smoother and more symmetric energy distributions.

However, increasing the wavelength without modifying the undulator parameters would move the system away from resonance. In order to maintain resonance at a different wavelength, the undulator strength parameter or period must be adjusted to satisfy the resonance condition. Since the resonant wavelength requires minimum power to achieve a desired energy spread, wavelength optimization must be considered when designing the undulator.

For example, to achieve resonance at a new wavelength of 1.6 microns, the current undulator configuration would not be applicable. The resonance condition indicates that a longer wavelength requires either an increase in the undulator period, an increase in the undulator strength parameter, or a decrease in the electron beam energy. The most practical modification would be to change the undulator period from five to ten centimeters, while maintaining the same beam energy and strength parameter. This could be realized with a variable period undulator in which internal motors adjust the spacing of magnetic poles to tune the effective undulator period.

CONCLUSIONS

The Laguerre-Gaussian laser heater experiment conducted by Tang et al. showed that an LG_{01} transverse mode produces a more Gaussian energy distribution and therefore reduces microbunching instability. The analysis in this review extended these ideas to examine how the wavelength of the laser heater affects this phenomenon. A wavelength that satisfies the resonance condition of the undulator maximizes the coupling between the laser field and the electron beam. This allows for the desired energy spread in the electron beam to be achieved with minimal laser power. Using a non-resonant wavelength reduces the modulation amplitude and weakens the microbunching suppression. Longer wavelengths can enhance smoothing by producing greater slippage, if matched with appropriately designed undulator parameters.

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