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Considering Spatial Light Modulators to Create Doughnut Shaped Intensity Beams

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Abstract: Review of Tang Jingyi, et Al. "Laguerre-Gaussian Mode Laser Heater for Microbunching Instability Suppression in Free Electron Lasers" and Discussion of New Ways of Generating LG_{01} modes using Computer Generated Holograms and Spatial Light Modulators

INTRODUCTION

In this article the authors investigate and experimentally demonstrate a new method for suppressing microbunching instability (MBI) in high-brightness free-electron lasers by modifying the transverse spatial profile of the laser-heater beam. Microbunching instability arises when high-charge electron beams are longitudinally compressed in the accelerator, producing small-scale energy and density modulations that degrade beam quality and limit the spectral performance of the FEL. Traditionally, laser heaters mitigate this effect by introducing a controlled amount of uncorrelated energy spread into the beam. Conventional heaters use a near-Gaussian infrared laser co-propagating with the electrons in a magnetic undulator. However, practical issues such as pointing jitter and finite laser-beam size often lead to a non-ideal "double-horn" energy distribution in the electrons, which reduces the efficiency of MBI suppression.[1]

To address this problem, the authors propose replacing the conventional Gaussian laser with a Laguerre–Gaussian LG_{01} mode, which possesses a characteristic doughnut-shaped intensity profile with a central minimum and a ring of higher intensity. In their configuration the electron beam is aligned to pass through the intensity minimum at the center of the LG beam. Because the electrons sample a region where the optical intensity varies smoothly and approximately uniformly, the induced energy modulation becomes more homogeneous across the bunch. This design avoids the double-horn structure that arises when electrons in a Gaussian heater encounter substantial spatial intensity gradients. The LG_{01} beam used in the experiment was produced by passing the heater laser through a spiral phase plate, enabling efficient and clean mode conversion at energies up to approximately 1.8 mJ per pulse.[1]

The authors conducted a series of measurements at the Linac Coherent Light Source to evaluate the impact of this new heater scheme. Using a high-resolution spectrometer immediately downstream of the heater undulator, they observed that the LG_{01} beam produced a near-Gaussian energy distribution across a wide range of induced energy spreads, including spreads exceeding those typically required for optimal MBI suppression. By contrast, the Gaussian heater rapidly produced double-peaked distributions as the laser power increased. Quantitatively, the energy distributions resulting from LG heating exhibited consistently higher agreement with Gaussian fits, demonstrating improved stability and a more uniform heating process.[1]

To examine the effect on microbunching, the authors analyzed coherent radiation emitted by the beam after acceleration to several GeV and after its passage through the bunch compressors. The resulting spectra indicated that high-frequency microbunching components were significantly suppressed when the LG_{01} heater was used, even when the induced rms energy spread was matched to that of the Gaussian case. The improved suppression translated into better performance of the FEL, particularly in soft-x-ray self-seeded configurations, where microbunching can introduce unwanted spectral features. In experimental operation of the seeded FEL at approximately 750 eV, the LG heater produced cleaner spectra with reduced sidebands, consistent with simulation predictions that indicated an improvement in spectral purity and bandwidth narrowing.[1]

The authors note that although LG heating introduces some dependence on transverse alignment—because the electron beam must pass through the central null of the optical mode—the demonstrated system functioned robustly under realistic pointing jitter. They conclude that structured-beam laser heating, exemplified by the LG_{01} mode, provides a practical and effective path toward improved control of microbunching in existing and future FEL facilities. Their work represents the first experimental demonstration that transverse beam shaping of the heater can directly enhance electron-beam quality and FEL output, suggesting broader opportunities for "second-generation" laser-heater designs employing non-Gaussian or otherwise tailored optical modes.[1]

METHODS

One area to expand on the study is to review how LG_{01} mode beams were constructed in the paper, other ways they can be constructed, and the upsides and downsides of each technique.

In order to create LG_{01} mode beams in the paper, the authors employed a spiral phase plate. The spiral phase plate is an optic that takes an input gaussian beam and outputs a LG_{01} mode beam [2]. The spiral phase plate is a diffractive optic with 16 steps of increasing thickness. The effect of the optic is an induced 2π phase shift across the beam and a resulting null in the center of the beam. Thus, the characteristic doughnut shaped beam is formed by the optic. Such an optic was chosen because of its ability to operate at high efficiency, high power conditions, which are necessary requirements for a laser heater of a free electron beam [2]. Therefore, the usage of such an optic follows from the parameters of the system, and ought be considered when considering the potentials of other LG_{01} mode beam generator.

Another optic that can be considered for this role is a computer generated hologram (CGH). At its simplest, the CGH is a recording of an interference pattern between the desired field and a reference field. Applying a gaussian beam on the axis of the interference pattern results in a far field pattern that resembles the desired beamshape[3]. To increase the conversion efficiency, and better maintain control of the amplitude and phase of a CGH, spatial light modulators (SLM) can be used to improve the production of a CGH, and thus produce a better doughnut shaped pattern [4]. Additionally, the combination has been previously reported as a good source of generating complex LG modes [5]. Therefore, comparing a CGH formed through a SLM to a spiral phase plate is of interest as a novel source of LG_{01} mode beams for a laser heater.

RESULTS AND INTERPRETATION

Liquid crystal SLM behaves similarly to the linear electro-optic effect, where an applied voltage creates a variation in the indexes of refraction in a bifringent media. The liquid crystal varies from the electro-optic effect because there is no longer a linear dependence on applied voltage, and the physics of a SLM allow for the intensity of light to be varied. The change in both phase and amplitude reflects liquid crystals having their susceptibility vary as a function of applied voltage. Thus, a modulating voltage shapes the phase and intensity, allowing for the creation of LG_{01} modes. Additionally, SLMs also rely on diffraction to modulate an incoming wave, where a modulated voltage across the grating creates a phase mask that modulates an incoming wave.

Practically, liquid crystal SLMs create a phase mask capable of modulating both the intensity and phase of a gaussian beam. The mask approximates the form of the LG_{01} mode, and is described by the following [6]:

$$\Phi_{\mathrm{SLM}} = f_{\mathrm{LG}} \cdot \sin(\Phi_{\mathrm{LG}} + G_x x + G_y y)$$

With Gx and Gy encoding the values of the grating in x and y coordinates, and Φ_{LG} describing the phase and amplitude values of a LG mode, and f_{LG} encoding the amplitude approximation of a LG mode through an inverse Bessel function of the amplitude. Unlike the SSP, this method of producing LG modes can be reconfigured by determining new values for Φ_{LG}, f_{LG}, Gx, and Gy [6].

However, such a method struggles with efficiency when compared to a SSP. Because a SSP is able to apply a continuous phase change to the entire applied beam, the resulting output is without error to parts of a beam. In contrast, a SLM relies on quantizing the encoded phase to pixels, which inherently creates an incomplete reconstruction of the desired mode. Additionally, each of these pixels have spacing between them, and that spacing means that the parts of the input beam that pass between the pixels are unaffected. Finally, the construction of the beam through a SLM creates diffraction order losses because power from the incoming beam is converted into other orders. The diffraction grating created creates other, higher order modes.

When considering a CGH as a replacement for the SPP, one parameter of interest in the case of the laser heater is the maximum beam power that can be produced through the optic without damaging it. Specifically, for the LCLS-II laser heater design would require up to 100 W of infrared power [2]. With recent advancements in liquid crystal SLMs, SLM CGHs have been able to reach power levels at 350 W, and would therefore meet the minimum power requirements of a laser heater, albeit near the upper limit of the cutting edge of liquid crystal SLMs. [7]

CONCLUSIONS

Laser heaters serve as an important device to control microbunching instability in a free electron laser. Controlling microbunching instability allows for free electron lasers to be both high gain and coherent light sources, making them incredibly useful devices to produce X-ray light capable of seeing and manipulating matter at very short (femtosecond) timescales.

The laser heater of a free electron laser relies on high power and high efficiency LG_{01} mode. While these modes have been produced in the paper using a SSP, a SLM created CGH has the potential to serve as a novel source of LG_{01} modes. With new advancements in cooling technology of Liquid Crystal SLMs allowing for the high power of laser heaters. SLMs lack the capability to match the output efficiency of SPP, but using an SLM also enables easy testing of more complex LG modes.

Understanding the capabilities of a SLM, The next steps would be to test it as a replacement to a SPP in a laser heater. The laser heater would need a new set of supporting optics to be fully implemented in a laser heater. Once implemented, comparative experimental tests can be performed to determine the performance differences between the optics. Should the SLM serve as a reasonable alternative to an SSP, other LG modes can be tested to determine their ability to control microbunching instability.

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