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THE ROLE OF LASER SHAPING IN MICROBUNCHING INSTABILITY SUPPRESSION AND SEEDED X-RAY FREE ELECTRON EMISSION

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Abstract

Microbunching instability (MBI) driven by collective effects in an accelerator is known to be detrimental for the performance of X-ray free electron lasers. At the Linac Coherent Light Source (LCLS), laser heater (LH) system was installed to suppress the microbunching instability by inducing a small amount of slice energy spread to the electron beam. The distribution of the induced energy spread greatly effects MBI suppression and can be controlled by shaping the transverse profile of the heater laser. In this paper, we present theoretical and experimental results on utilizing a Laguerre-Gaussian 01 Mode (LG01) laser at LCLS to obtain better suppression of the instability. We demonstrate experimentally that Gaussian-shaped energy distribution is induced by LG01 mode LH and final microbunching gain is better suppressed. We finally discuss the role of LH spatial shaping in soft X-ray self-seeded (SXRSS) FEL emission and demonstrate that this LH configuration is capable of generating high spectral brightness FEL pulses.

INTRODUCTION

Control and reduction of microbunching instability (MBI) is central to accelerator physics and accelerator-based light sources, particularly free electron lasers (FEL) [1]. In a linear accelerator, MBI arises primarily from the interplay between longitudinal space charge of an electron beam (e-beam) and energy-dispersion correlations in e-beam optics. MBI is known to degrade emission performance of X-ray FELs and can be well suppressed from stochastic heating using a laser, namely a laser heater (LH). At the Linac Coherent Light Source (LCLS), the LH consists essentially of an electron beam undulator and a co-propagating infrared (IR) laser that modulates and increases the energy spread of the e-beam by about one order of magnitude and without exceeding FEL tolerances [2]. The shape and magnitude of this modified e-beam energy distribution depends highly on the transverse intensity distribution of the IR laser. The current laser at the LCLS LH employs a Gaussian transverse beam distribution, which has shown to partially suppress MBI and result in a greater FEL intensity by an order of magnitude [3].

Recent theoretical studies have investigated cylindrically symmetric and other non-conventional laser beam shapes to provide better suppression of microbunching [4–6]. For instance, a transverse Laguerre-Gaussian 01 (LG01) mode provides a mathematically ideal solution to suppressing MBI. This beam mode has been proposed because under ideal laser and electron beam conditions the suppression of microbunching is at best more than 23 times better than that of an equivalent transversely Gaussian laser.

Here, we present the first experimental demonstration of effective MBI suppression using a LG01 transverse mode laser at the LCLS LH, and we compare the improved results with respect to MBI suppression using the Gaussian-shaped laser. The effects on MBI suppression are characterized by multiple downstream measurements, including analysis of the e-beam's longitudinal phase space and coherent radiation spectroscopy. We also experimentally investigate its impact on soft X-ray self-seeded (SXRSS) FEL emission, one of the most advanced operation modes of a FEL for which controlled suppression of MBI is critical [7].

METHODS AND RESULTS

The LH transverse profile, originally Gaussian at LCLS, was converted to a LG01 distribution using a 1-inch diameter spiral phase plate (SPP), as in Fig. 1. The SPP is a diffractive optic with 16 steps, each of increasing thickness, circumferentially around the plate resembling a spiral stair case. This spiral stair case writes an increasing spiral phase onto the beam for a total phase change of 2π. The polarization of the laser is unaffected by this type of diffractive optic since the SPP only effects the phase structure of the beam. A short distance after interaction with the plate, a null in the field amplitude at the center of the laser due the phase singularity is generated and is maintained as the laser propagates. For best diffractive efficiency, two Galilean telescopes were placed before and after the SPP to fill the full clear aperture and then to restore the laser to proper size for propagation to the undulator respectively.

The first diagnostic, directly downstream of the LH where the e-beam's energy is 135 MeV, is a longitudinal phase-space spectrometer. The slice energy distribution is extracted from the central time slice of the streaked e-beam. For either transverse shape, the width of the energy distribution can be tuned by varying the IR laser energy. However, the Gaussian laser distribution is known and measured to provide a double-horn structure instead of an ideal Gaussian-like e-beam energy distribution for best energy suppression. We prove, according to our simulation, that we can achieve Gaussian-like e-beam heating with varying width by simply tuning the LG01 mode energy. Figure 2 shows that we can heat the e-beam up to 68 eV energy spread (Fig. 2(a)) while preserving a Gaussian energy distribution (Fig. 2(b-e)). We would like to note that when the e-beam is heated to 20-

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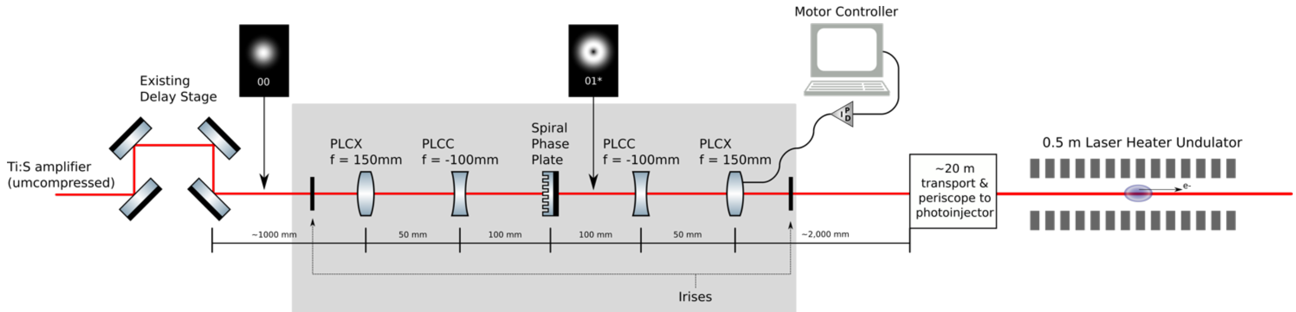

Figure 1: Simplified optical mode-conversion and control systems schematic, and transport to the laser heater undulator at the LCLS photoinjector

35 keV, resembling optimal LCLS operation conditions, the Gaussian energy distribution indicates its potential for better microbunching suppression and improved FEL performance.

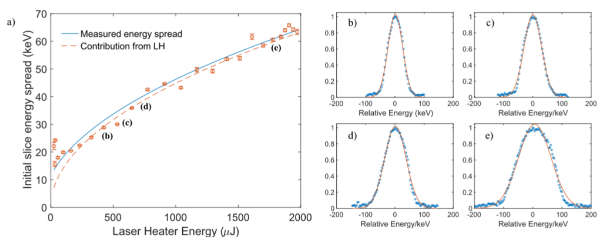

Figure 2: (a) Slice energy spread of the e-beam after the laser heater as a function of LG01 beam energy; and (b-e) four examples energy distributions in (a) with 25.1 (b), 30.3 (c), 36.8 (d), and 55.7 (e) keV energy spread and their corresponding Gaussian fits.

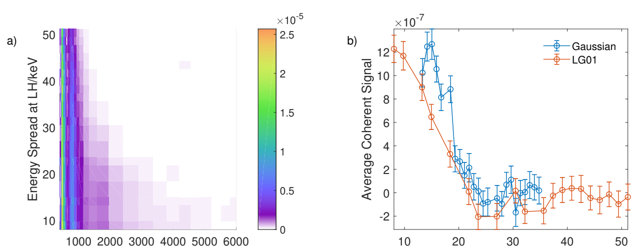

Figure 3: a) 2D-MIR spectrograph as a function of induced energy spread by LG01 transverse mode LH and b) integrated MIR spectral intensity for $k \in (3000, 5000)\,\mathrm{cm}^{-1}$ as a function of induced energy spread by both the LG01 and Gaussian mode LHs.

The second primary diagnostic, further downstream of linac where the e-beam reaches its final energy of 4 GeV, is a mid-infrared (MIR) spectrometer [8]. The MIR spectrometer enables characterization of microbunching at high space frequency from the e-beam's coherent secondary emission. A 2D-MIR spectrograph as a function of induced energy spread is show in Fig. 3(a). The strength of differing MIR frequencies map longitudinal charge density. That is, the lower MIR frequency range components represent the e-beam as a whole, whereas the higher frequency components correspond to shorter longitudinal density spikes (microbunching). The coherent spectral signal integrated along $k \in (3000, 5000)\,\mathrm{cm}^{-1}$(2–3.3 µm wavelength) is shown in red in Fig. 3(b) (Gaussian mode LH in blue for comparison). Here, a lower spectral signal contribution signifies reduction of MBI. In the range of 15–20 keV energy spread, the LG01 shows significantly better MBI suppression compared to its Gaussian equivalent.

While effective MBI suppression can significantly improve a vast number of FEL operational modes, one of its major applications resides in increasing self-seeded spectral monochromaticity and brightness. Theoretical and experimental analyses have indicated that the pedestal structure in SXRSS spectrum is connected with MBI, which dramatically reduces the achievable resolution in a number of ultrafast X-ray spectroscopic techniques. In our experiment, we achieve SXRSS operation at LCLS at 750 eV photon energy employing the LG01 LH, where numerous shots show high sideband suppression, as exemplified in Fig. 4(a). We also show that the fraction of FEL power within 1 eV bandwidth is increased from 0.5 to 0.9 when the LG01 energy is increased (Fig. 4(b)), which indicates that new transverse mode laser heater works in reducing the sidebands and suppressing the microbunching.

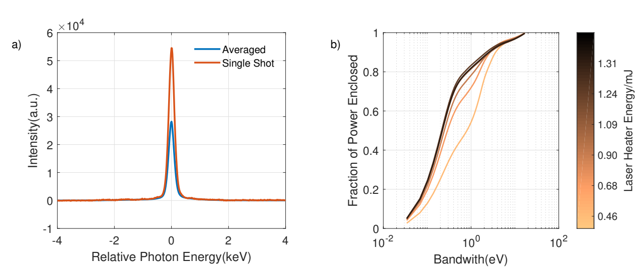

Figure 4: a) Averaged (red) and single shot (blue) SXRSS spectral distributions centered at 750 eV photon energy, and b) fraction of SXRSS spectral power as a function of bandwidth for varying LG01 mode energy in the LH.

DISCUSSION: EFFECT OF JITTER

For Laguerre-Gaussian laser heater, transverse jitter can have a significant impact on the induced energy distribution.

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Acoustic and thermal noise can cause both pointing and transverse offset jitter in the LH pointing, thus compromising LH and e-beam spatial overlap from shot to shot, especially for LG01 mode with high laser energy. Due to random jitter, the e-beam may occasionally overlap with the intensity minimum in the center of the laser, and other times lie along the intensity maximum at the ring. As studied in [4,5], the LG01 mode can generate a perfectly Gaussian energy distribution in ideal, mode-matched conditions. However with strong jitter, laser distribution around the electron beam is equivalent to a flattop transverse distribution, which inevitably results in the double-horn energy distribution. Besides, at the ring of the laser undesired large energy spread could be induced considering the high maximum power of LG01 mode laser.

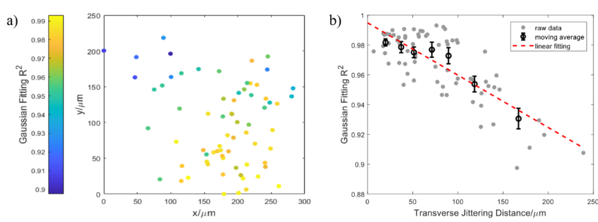

Figure 5: Influence of transverse laser jitter for LG01 mode laser heater. (a) Positions of laser center on the camera of different shots with Gaussian fitting R^2 of theirs corresponding induced energy distributions. (b) Correlation between the Gaussian fitting R^2 of the energy distribution and radial distance laser jittering away from the optimal position.

To verify our analyses and quantify the jittering effects, we utilize an online camera imaging the interaction point in the LH [2] in order to non-intrusively determine the transverse position fluctuations due to pointing noise. The data is collected simultaneously with the longitudinal phase space spectrometer so that the induced energy spread can be correlated with the laser transverse jitter. We would like to note that the e-beam transverse jitter is negligible compared to that of the laser. Figure 5(a) is representative of the transverse jitter, which amounts to 100 μm rms, and shows a number of consecutive central position of the laser beam in the LH undulator. For each shot, the induced energy distribution is recorded by spectrometer. Yellow dots show position of shots with Gaussian-shaped energy distribution while green and blue are those with less Gaussian and double-horn distributions. The shots of different distribution shapes are segregated in the transverse plane which indicates that correlation exists. We define the optimum position of the laser by averaging the positions of the "good shots" and plot Gaussian fitting R^2 as a function of radial distance the laser jitters away from this optimum position. As shown in Fig. 5(b), correlation between the distribution structure and the jittering distance verifies our previous analyses and signifies that large transverse jittering can deteriorate the LG01 mode laser heater performance.

CONCLUSIONS AND OUTLOOK

We experimentally demonstrate that a LG01 transverse mode LH induces a Gaussian energy distribution of the e-beam and show evidence of improvement on MBI suppression compared to routine operations. We have also studied the impact of the LG01 LH on SXRSS performance and its monochromaticity or spectral brightness. These results will fuel the next generation of engineered laser heater design for existing and future augmented brightness linacs and X-ray FELs.

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