Laser Heater Shaping for Microbunching Instability Suppression in Free Electron Lasers

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Abstract: We present two laser heater shaping solutions based on Laguerre-Gaussian and discrete beamlet array distributions that significantly outperform current microbunching instability suppression approaches in free-electron lasers.
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1. Introduction and Motivation

The microbunching instability (MBI) is known to degrade emission performance in free-electron lasers (FEL). This instability can be suppressed by increasing the uncorrelated energy spread of the electron bunch with either a superconducting wiggler or a laser heater (LH)[1]. At the Linac Coherent Light Source (LCLS), the LH increases the energy spread of the electron bunch by an order of magnitude without exceeding FEL tolerances. Heating occurs along a small undulator within a magnetic chicane at an e-beam energy of 135 MeV. The e-beam energy distribution after the LH is highly dependent on the transverse profile of the LH beam. The current LH at LCLS employs a Gaussian transverse beam distribution, which has shown to successfully suppress the MBI and result in a greater FEL intensity by an order of magnitude[2]. A Gaussian laser profile will most effectively suppress MBI when the laser diameter is $\sqrt{2}$ larger than the electron diameter, which is the mode-matching condition. In practice, when non-negligible transverse offset jitter between laser and electron beams is present in the LH, the laser can be increased slightly to the detriment of the electron energy distribution[1].

Recent theoretical studies have investigated Laguerre-Gaussian (LG) and other unconventional transverse beam distributions that may provide better suppression of microbunching[3]. For instance, the LG01 mode has been proven to provide 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 better than that of the mode-matched Gaussian laser. Here, we examine the effect transverse jitter and beam ellipticity on energy distributions induced by the current LH to resemble realistic beam operations at FELs based on routine LCLS operations as our case study. The qualitative results are transferable to other x-ray FELs. Under these practical considerations, we explore alternative LH designs that outperform state-of-the-art LH architectures based on LG01 beams and an array of small Gaussian beamlets, henceforth referred to as Beamlet Array (BA).

2. Methods and Results

We calculate the modified electron distribution and suppression factor after the laser-electron interaction by modeling transverse interactions between an arbitrary transverse laser distribution and the electron bunch. Our calculations do not account for longitudinal effects, such as temporal chirp or space charge effects. Due to the high energy of the electrons at the end of the photo-injector, where they interact with the laser in the LH undulator, these effects are negligible. We add both transverse offset jitter of ~200 um and 3:1 ellipticity to the electron bunch. Offsets and pointing angles are generated with random Gaussian noise. The e-beam size is kept the same, while the LG01 and BA dimensions and powers are optimized for the LH performance.

The modified electron distributions are displayed in Fig. 1 for both LG01 (Fig.1.a) and BA (Fig.1.c) cases. The red curves on Fig. 1.b/d delineate the mode-matched scenario for each laser distribution, while the black overlay curves represent possible energy distributions resulting from transverse offset jitter and electron bunch ellipticity. The energy distribution that best matches a Gaussian linewidth with ~20 keV energy spread is the benchmark metric at LCLS. From these results, the mode-matched LG01 distribution ideally matches the LCLS benchmark at FWHM, while the BA distribution results in a less ideal Lorentzian-like lineshape. The suppression factors calculated for the Fig.1.b distributions also favor the LG01 distribution by about one order of magnitude over the BA. However, the jitter- and ellipticity-induced deviation from the mode-matched distribution can be severe for LG01, as shown in Fig.1.b, a feature that is overcome by design using the BA distribution.

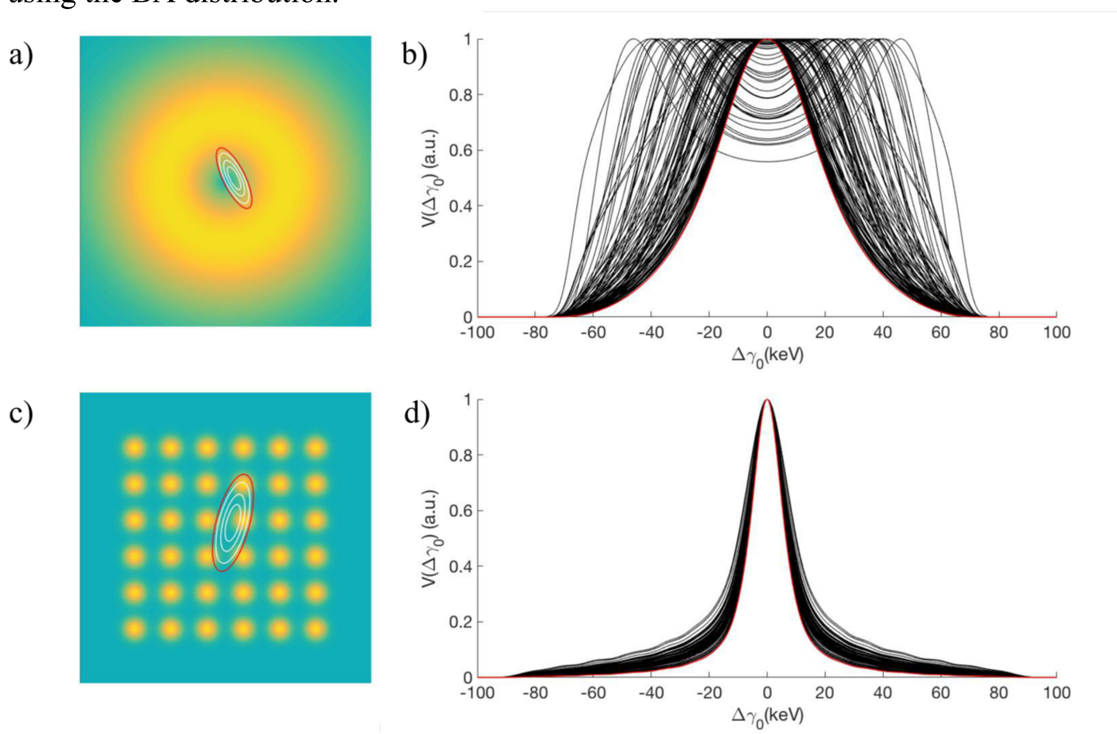

Fig. 1: a) LG01 laser and **b)** corresponding electron bunch energy redistribution ($\Delta\gamma_0$) overlays, and **c)** BA laser and **d)** corresponding electron bunch energy redistribution overlays for a 3:1 ellipticity electron bunch (in contour lines) with random transverse offset jitter.

3. Conclusions

We present two laser distribution solutions to dramatically improve MBI suppression in FELs. The LG01 distribution is perfect under ideal conditions, while the BA trades MBI suppression efficacy for high tolerance against routine operational and experimental conditions.

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