Title

Alternative Methods of Producing Donut-Shaped Intensity Beams with Fixed Polarization in the Study of Laguerre-Gaussian Mode Laser Heater

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Alternative Methods of Producing Donut-Shaped Intensity Beams with Fixed Polarization in the Study of Laguerre-Gaussian Mode Laser Heater

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Abstract: This paper reviews the topic of using laser heater (LH) mode in free-electron lasers (FELs) to suppress microbunching instability (MBI). It will also explore alternative methods for producing donut-shaped intensity beams with fixed polarization.

INTRODUCTION

Free-electron lasers (FELs) utilize relativistic electron beams to generate ultrashort, high-brightness coherent radiation. However, the microbunching instability (MBI) of the electron beam can diminish its quality, adversely affecting the gain and brightness of the FEL. In this context, the laser heater (LH) introduces energy diffusion through laser modulation, thereby suppressing MBI. The effectiveness of this suppression is closely related to the lateral shape of the laser pulse. Currently, the LH system employs a Gaussian-shaped laser beam; however, lateral jitter can produce a double-horn energy distribution, rendering it less effective in suppressing MBI. Studies have shown that a laser beam utilizing a transverse Laguerre-Gaussian (LG) mode can more effectively control the energy distribution, leading to improved MBI suppression and enhanced FEL performance.

While the LG mode has shown promising results, alternative methods, such as all-fiber structures, also offer potential solutions in the process of generating donut-shaped beams.

METHODS

The study used optical mode conversion, using a spiral phase plate (SPP) to convert Gaussian laser light into LG transverse mode to generate a ring-shaped light intensity distribution, as shown in Figure 1. In this process, the transmission efficiency of SPP exceeded 95%.

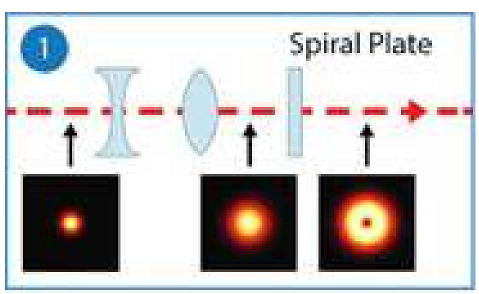

Figure 1: Spiral Phase Plate (SPP) Mode Conversion.

Optical tweezers, all-fiber structures, and engineered microspheres are three alternative methods for generating donut-shaped intensity beams. Optical tweezers use a focused laser beam to capture and manipulate particles, all-fiber structures employ optical fibers to generate specific beam patterns, and engineered microspheres apply optical resonances to modify light propagation and light-matter interactions. In this paper, I will discuss the potential alternative method of using all-fiber structures to generate donut-shaped intensity beams.

Unlike SPP conversion, the all-fiber structure uses mode-selective couplers (MSC) as the mode converters to generate donut-shaped intensity beams. The MSC transforms the fundamental mode (LP01) into a first-order donut-shaped mode, after which the polarization controller (PC) adjusts the polarization states. As the MCF is heated and tapered, the light is evenly distributed across the surrounding cores, resulting in a donut-shaped beam with uniform power distribution. The process is shown in Figure 2.

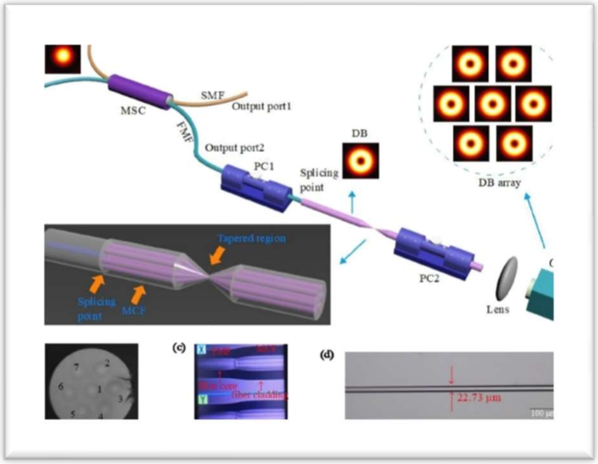

Figure 2: (a) Experimental setup for donut beam generation. (b) MCF cross section. (c) Splicing point. (d) Tapered MCF region.

RESULTS AND INTERPRETATION

The LG laser heater effectively induces a Gaussian energy distribution across a broad range of energy broadenings, significantly outperforming the conventional Gaussian laser heater at the optimal energy broadening (20–30 keV). As a result, the LG mode enhances the FEL spectral monochromaticity by 20% within the 1 eV range.

Compared to the spiral phase plate method, the all-fiber approach offers advantages such as low insertion loss, low cost, high mode conversion efficiency, high stability of the point spread function against environmental disturbances, and good alignment tolerance. However, it requires a more complex manufacturing process due to the need for specialized optical fibers. Nonetheless, it still holds great potential for future applications.

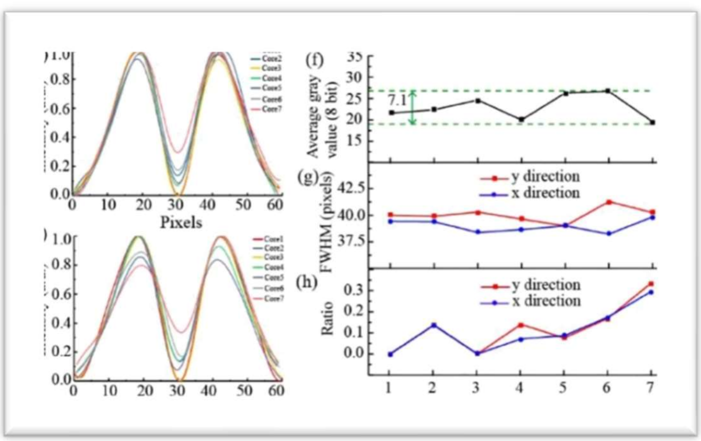

Figure 3: Detailed analysis of the donut beam profiles in the setup.

Figure 3 provides a detailed analysis of the doughnut-shaped beam profile, demonstrating consistent power distribution and beam quality across the seven cores.

The power transfer process is simulated based on coupled-mode theory. The conventional coupled-mode theory, neglecting higher-order terms for an MCF with n cores, is expressed as follows:

$$\frac{dA_m(z)}{dz} = -j\beta_m A_m(z) + j\sum_{l=1}^{n} p_{mn} A_l(z) \qquad m = 1, 2, 3 \ldots n$$

The mode amplitude in core m is shown as $A_m(z) = a_m(z)\exp(-j\beta_m z)(-j\beta_m z)$, where z is the propagation direction, p_{mn} is the mode coupling coefficient from core m to core n, and β_m is the propagation constant of core m. And after substitution and problem solving, we get:

$$P_n(z) = C \cdot a_n \cdot a_n^* = C\{0 - 4\sum_{i=1,j=1}^{i=n,j=n} l_{ni} l_{nj} h_{1i} h_{1j} sin^2[(\frac{\gamma_i - \gamma_j}{2})z]\}, i \neq j$$

The initial condition states $a_1(0) = a_0$, $z = 0$ and $a_0(0) = 0$, $n \neq 1$, the coefficients related to the input power is shown as l_{ni} and h_{ni}, and C is from the cores' distribution. The final approach of the all-fiber structure offers a high mode conversion efficiency of 94%, low insertion loss of less than 0.5 dB, and a wide bandwidth of approximately 100 nm.

CONCLUSIONS

Experiments have shown that transverse-mode laser heaters (LH) can generate a Gaussian energy distribution in the electron beam across a broad dynamic range, while also improving microbunching instability (MBI) suppression. These results provide valuable insights for the design of next-generation laser heaters and support the development of high-brightness linear accelerators and X-ray FELs. Additionally, the all-fiber method provides an alternative for generating donut-shaped beams, with benefits such as low insertion loss, high mode conversion efficiency, and enhanced stability.

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