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Investigation into Alternate Sources of Laguerre-Gaussian Modes for Microbunching Instability Suppression

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Abstract: Theoretical calculations and arguments surrounding the use of spatial light modulators in the place of laser heater undulators in the creation of Laguerre-Gaussian modes to prevent microbunching instability in free electron lasers.

INTRODUCTION
Free-electron lasers are at the forefront of prominent scientific and industrial fields surrounding imaging of small ultrafast processes. A free-electron laser is a laser that generates high-intensity, coherent electromagnetic radiation utilizing a high-energy beam of electrons [1]. These lasers in the combination of extreme brightness and short pulses of radiation allow us to image objects on the molecular and even the atomic level which reveal fundamental laws of physics.

However, as these lasers are susceptible to microbunching instability (MBI) defined as longitudinal instability that leads to dynamical deformations of the charge distribution in the longitudinal phase space [2]. The research presented by J. Tang et. al, provides a new method to reduce the effects of MBI with a Laguerre-Gaussian Mode Laser Heater which purposefully broadens the laser signal in a Gaussian distribution. This then drowns out and suppresses the MBI. In the creation of the Laguerre-Gaussian modes, it is important to note that there is the effect of transverse jitter effects that end up negatively affecting the induced energy distribution [1]. Here we discuss alternative solutions to create Laguerre-Gaussian modes to eliminate this effect.

METHODS
A Laguerre-Gaussian mode is a specific subset of Gaussian distributions called Hermite-Gaussian functions. The Laguerre-Gaussian mode is in the form of cylindrical coordinates hence why the shape of it is like a donut, showcased in Figure 1.

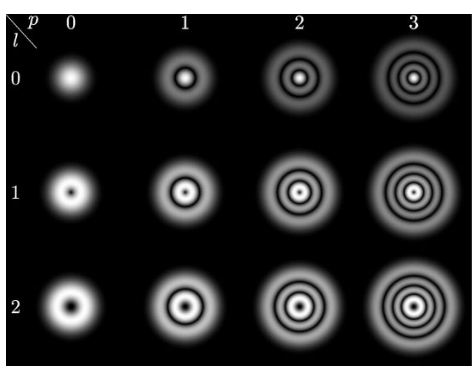

Figure 1: Spatial energy distribution for Laguerre-Gaussian modes [3]

The paper [1] uses the Laguerre-Guassian 01 (LG_{01}) mode specifically to induce an energy spread as this matches previous beam forming into a donut shaped energy distribution. If we want to replace the laser heating undulator with something better, we need to be able to generate the same LG_{01} distribution. The equation that defines these Laguerre-Gaussian distributions is an adaptation of the Gaussian distribution instead in cylindrical coordinates. The equation is presented below:

$$u(r,\phi,z) = C_{lp}^{LG}\frac{1}{w(z)}\left(\frac{r\sqrt{2}}{w(z)}\right)^{|l|}\exp\left(-\frac{r^2}{w^2(z)}\right)L_p^{|l|}\left(\frac{2r^2}{w^2(z)}\right)\ \exp\left(-ik\frac{r^2}{2R(z)}\right)\exp(-il\phi)\ \exp(i\psi(z)),$$

In the equation, p represents the radial index while l represents the azimuthal index that can be positive, negative, or zero. Both of which are the major determinants of the distribution types reflected in Figure 1, shown with only positive l's.

Now, to generate this type of distribution without using the laser heater, we can instead use a Spatial Light Modulator (SLM) which uses physical principles such as crystal or mirror orientation to modulate the light passing through the device. They operate on complex software configurations, for our purposes we will simplify calculations by thinking about matrix multiplication of electric field elements in the beam to produce the donut-shaped distribution we are looking for. If we have a linearly polarized wave in the form of a vector:

$$\begin{bmatrix} cos(\alpha) \\ sin(\alpha) \end{bmatrix}$$

Where alpha is the offset from the x-axis of the system. We can operate on this vector using the Jones matrix below where theta is a programmed azimuthal angle that will operate on the light.

$$\begin{bmatrix} cos(\theta) & sin(\theta) \\ sin(\theta) & -cos(\theta) \end{bmatrix}$$

Which creates the result:

$$\begin{bmatrix} cos(\theta) & sin(\theta) \\ sin(\theta) & -cos(\theta) \end{bmatrix}\begin{bmatrix} cos(\alpha) \\ sin(\alpha) \end{bmatrix} = \begin{bmatrix} cos(\theta)cos(\alpha) + sin(\theta)sin(\alpha) \\ sin(\theta)cos(\alpha) - cos(\theta)sin(\alpha) \end{bmatrix} = \begin{bmatrix} cos(\theta - \alpha) \\ sin(\theta - \alpha) \end{bmatrix}$$

And thus, our wave is now in a circular distribution with a variable that controls the polarization of the wave which is constant throughout. These calculations are supported by a similar argument presented by J. Zhao et. al on creating cylindrical light distributions using a vector wave plate [4]. A graphic showing this transformation is below:

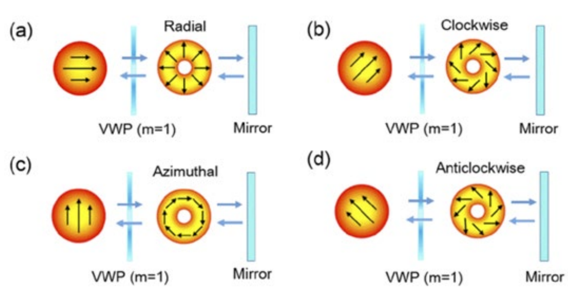

Figure 2: Linear Polarization to Donut Shaped Distributions using a vector wave plate [4]

RESULTS AND INTERPRETATION

With the demonstrated potential of turning a linearly polarized wave into a wave with circular distribution, we can easily extrapolate these mathematical principles to more complex models to effectively create the LG_{01} distributions we are looking for. Thus, we do not have to rely on the laser heater undulator which can be susceptible to transverse jitter effects.

In the topic of Spatial Light Modulators (SLMs) the type that would be most applicable to the Linac Coherent Light Source (LCLS) laser from the paper [1] would be a Liquid Crystal on Silicon (LCOS) SLM. The LCOS SLM uses liquid crystals on silicon to modulate light to create the unique light patterns they are programmed for. The benefits of using a LCOS SLM include a high spatial resolution, low power consumption, and phase modulation of both amplitude and phases of light. On the contrary, LCOS SLMs have a few drawbacks including the limited wavelength range of the liquid crystal materials and temperature sensitivity that affects performance and stability.

Nonetheless, the programmability and ability to filter a variety of modes shows the promise of SLM applications in generating these LG_{01} signals and creating this induced energy spread. One such demonstration of this potential is presented by J. Hong in his PhD dissertation utilizing LCOS SLMs specifically to create phase and polarization modulations of images such as text and characters [5] indicating how these SLMs can be used to create LG_{01} distributions as accurately as the sharp edges of characters.

CONCLUSIONS

The Laguerre-Gaussian mode used to induce an energy spread in the laser to make sure that MBI is suppressed later down the line is a monumental finding, however, there are still some cases where transverse jitter causes the laser to revert to normal energy distributions and still be affected by MBI. A potential alternative is replacing the laser heater undulator with a Spatial Light Modulator that can dynamically shape light into whatever distribution it is programmed for. Proved through demonstrated calculations from linear polarization to circular distributions, these alternatives could serve to eliminate the effects of the transverse jitter while maintaining the MBI suppression presented in the paper [1]. The next step would be testing to see if the benefits of replacing the laser heater undulator with a Spatial Light Modulator system provides increased performance worthy of trading this proven system.

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