ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPG72

STUDY ON HIGH ENERGY COUPLING EFFICIENCY OF LASER-ELECTRON INTERACTION VIA VORTEX BEAM*

Xiazhen Xu, Haoran Zhang†, Zixin Guo, Jingya Li, Zhigang He, Qika Jia, Duohui He
National Synchrotron Radiation Laboratory,
University of Science and Technology of China, Hefei, Anhui, China

Abstract

Manipulation electron beam phase space technology by laser-electron interaction has been widely used in accelerator-based light sources. The energy of the electron beam can be modulated effectively under resonant conditions by using an intense external laser beam incident into the undulator together with the electron beam. Enhancing the modulation efficiency is crucial for the performance of high repetition rate seeded free electron lasers (FELs) and other related devices. In this paper, we propose a new scheme to augment the efficiency of laser-electron interaction by employing the interaction between a vortex beam and an electron beam within a helical undulator. Three-dimensional time-dependent simulation results indicate that the modulation repetition rate of laser-electron interaction using a vortex beam can be improved by one order of magnitude over the conventional Gaussian beam at the same input power.

INTRODUCTION

Accelerator-based light sources stimulated progress in photon science in a truly extraordinary manner. Among them, the laser modulation technique through the undulator is widely used to manipulate the distribution of the electron beam, so as to control the radiation characteristics. Using the laser-electron interaction to finely manipulate the electron beam phase space has been widely used in accelerator sources such as echo-enabled harmonic generation (EEHG) free electron laser (FEL) and terahertz (THz) sources storage ring [1, 2]. Superconducting linac and storage rings can provide a high repetition rate electron beam for high average power coherent radiation. But for the laser system used to modulate electron beams, the repetition rate is limited because the laser system cannot support sufficient pulse energy at high repetition rates (~MHz).

For this reason, several seeded schemes enabling operation at a high repetition rate are proposed. One of the effective methods is to employ optical methods such as using an optical parametric chirped-pulse amplifier (OPCPA) system to increase the average power of the laser or laser cavity modulator. It has been reported a 100 kHz, sub-20 fs optical laser system delivering 88.6 W average power at a center wavelength of 800 nm for high-repetition-rate experiments at the LCLS X-ray free-electron laser [3]. The modulation repetition rate of seed laser can be improved by using laser cavity modulator [4]. The propagating radiation fields bounce back and forth among the mirrors in the cavity modulator. The repetition rate is no longer limited by the seed laser, but determined by the cavity. However, due to the material's optical damage threshold and energy loss, the repetition rate still cannot reach MHz.

Another more effective way is to reduce the laser power requirement for a single modulation, so that the high repetition rate of the seed laser can relatively easily to be berealized, such as electron beam self-modulation scheme[5]. In this scheme, a low-power seed laser weakly modulates the electron beam within a short undulator first, which forms density modulation in the subsequent dispersion section. Then, the electron beam traverses the second undulator, wherein the energy modulation is enhanced by the radiation emitted from the previously weakly bunched electron beam. However, it is highly dependent on the coherent radiation intensity in the self-modulation because it is modulated by the radiation emitted from the previously weakly bunched. Moreover, the addition of a modulation and chicane makes the device too complicated.

In this paper, we report the the electron beam interacts with vortex beam in a helical undulator. Higher energy modulation efficiency can be achieved by matching the transverse trajectory of the electron beam with the high energy region of the vortex beam field , so as to relax the power requirement of an external seed laser by more than an order of magnitude. This will help further understand the laser-electron interaction with high energy modulation efficiency and promote the development of advanced light sources such as high repetition rate free electron lasers.

VORTEX LASER-ELECTRON INTERACTION IN A HELICAL UNDULATOR

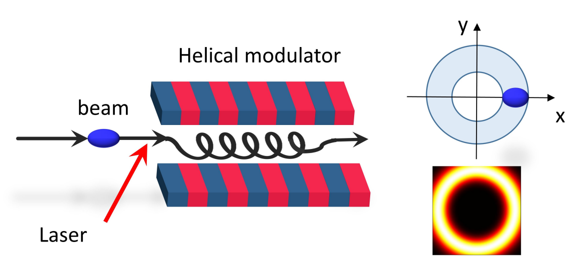

Figure 1: Modulation process. The x-y plane motion trajectory of the electron beam and the transverse distribution of the vortex beam field are displayed on the right.

* Work supported by the Youth Innovation Promotion Association (CAS).
† zhrzhm@ustc.edu.cn

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPG72

The energy of the electron beam is modulated by the interaction with the optical field of the seed laser in the undulator and the resonance condition as

$$\lambda_L = \frac{L_u}{2\gamma^2}\left(1 + K^2\right) \tag{1}$$

where λ_L is resonance wavelength, L_u is undulator period length, γ is the relativistic factor of electron beam energy, K is the helical undulator strength parameter, In order to increase the repetition rate of the laser-electron interaction, vortex beam is used to modulate the electron beam in the helical modulator. As shown Fig. 1, the transverse motion of electron beam can be regarded as circular motion due to the action of periodic magnetic field in helical undulator. Higher energy modulation amplitude is achieved by matching the high field intensity region of the modulated vortex beam field with the trajectory of the electron beam.

Generation of Customized Vortex Beam

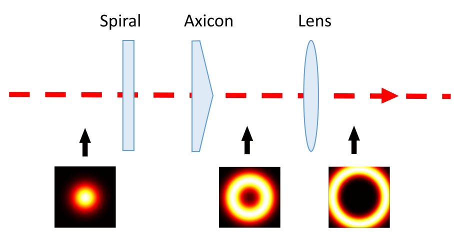

Figure 2: Generation of customized vortex beam.

A perfect vortex beam (PVB) is a propagating optical field carrying orbital angular momentum (OAM) with a radial intensity profile that is independent of topological charge [6]. Figure 2 shows a typical well-aligned optical setup consisting of a spiral phase plate, an axion, and a lens to generate a perfect vortex beam. First, the Laguerre-Gaussian (LG) beam is formed after the Gaussian beam passes through the spiral phase plate, and then passes through the axial prism to transform into the Bessel-Gaussian (BG) beam, and finally passes through the thin convex lens to make the Fourier change of light field to obtain the PVB. A customized vortex beam can be obtained by adjusting the axial prism parameters and lens focal length to modulate the spot size and ring width, and its transverse electric field distribution can be written in polar coordinates (r, θ) as:

$$E_{CV}(r,\theta) = i^{l-1}\frac{\omega_g}{\omega_\varepsilon}\exp(il\theta)\exp\left(\frac{-(r-R)^2}{\omega_\varepsilon^2}\right) \tag{2}$$

where l is the topological charge, ω_g is the waist of the input Gaussian beam, ω_ε is the waist of the Gaussian beam in the rear focal plane, $R = \varepsilon k_r f/k$ is the radius of the PVB, ε determines the ellipticity of PVB, here we only consider the case of $\varepsilon = 1$. k_r is the radial wavenumber relating to the numerical aperture (NA) of the axicon., k is the wavevector in free-space and f is the focal length of the Fourier transform lens. Given the fixed values of three parameters (ε, f, NA), the shape of PVB can be determined and is independent of the topological charge.

Laser-electron Interaction Theory

The energy modulation induced by laser-electron interaction is obtained in

$$\Delta\gamma(s) = \sqrt{\frac{P_L}{P_0}}\frac{2KL_u\,[JJ]}{\gamma w_0}f(s) \tag{3}$$

where P_L is the peak laser power, which is proportional to the square of the electric field strength E_{CV}, $P_0 = I_A mc^2/e \approx 8.7\text{GW}$, w_0 is the rms spot size of the laser, $[JJ] = J_0(\xi) - J_1(\xi), \xi = k_s K^2/\left(8k_u\gamma^2\right) = K^2/\left(4+2K^2\right)$, s is the radial position of the electron and $f(s)$ describes any arbitrary transverse profile of the laser beam.

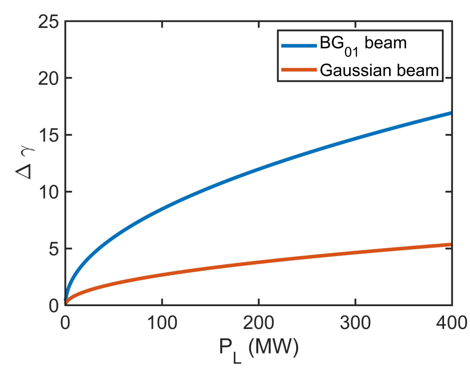

Figure 3: Variation of energy modulation amplitude with laser peak power. Two cases of BG_{01} beam and Gaussian-beam are obtained with the waist radius w_0 = 100 µm and 500 µm but the same wavelength λ=800 nm.

For the Gaussian beam, in order to consider the transverse amplitude of the electron beam in the undulator and the limitation of Rayleigh length $Z_r = \pi w_0^2/\lambda$ (Rayleigh length should be greater than the modulation distance), the optical waist size is usually designed to be larger. For Bessel-Gaussian 01 (BG_{01}) mode beam, however, there is no Rayleigh length limitation because the BG_{01} beam demonstrates diffraction-free propagation which means that it can travel a long distance from the electron beam in the undulator. Matching the transverse ring radius and ring width of the BG_{01} beam with the transverse trajectory of the electron beam can effectively improve the energy coupling efficiency between laser and electron beam. The numerical results according to Eq.3 are performed in Fig. 3 with different input laser peak power. The electron energy is 800 MeV, and the electron beam resonates λ_L = 800 nm in the undulator. The electron beam underwent 10 cycles of energy modulation and the total length of the undulator was 1 m. It can be seen that the modulation amplitude of BG_{01} beam interacting with the electron beam is higher than that of the Gaussian beam.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPG72

SIMULATION

To illustrate the possible application of the proposed scheme under real parameters, we take the Hefei light source-II (HLS-II) storage ring as an exemplar, and the relevant parameters are shown in Table 1. The simulation of the modulation process is carried out by the General Particle Tracer, a particle motion simulation software.

Table 1: Simulation Parameters

Parameter	**Value**
Beam energy	800 MeV
Beam energy spread	4.710^{-4}
Transverse electron beam size	50 µm
Transverse Gaussian laser size	500 µm
Transverse BG_{01} laser size	100 µm
Undulator parameter K	6.1819

The BG_{01} pulses are directed into the undulator, aligning the fundamental undulator wavelength in resonance with the laser wavelength of $\lambda_L = 800$ nm and a stretched duration $\tau_L = 0.5$ ps. The transverse amplitude of the electron beam moving in the undulator $\Delta x = \lambda_u K/2\pi\gamma \approx 62.8$ µm. Considering the electron beam size of 50 µm, we set the BG_{01} beam radius at 100 µm to ensure that the laser high field intensity region matches the electron beam transverse position. Then the electron beam is introduced a sinusoidal modulation in the undulator by laser-electron interaction.

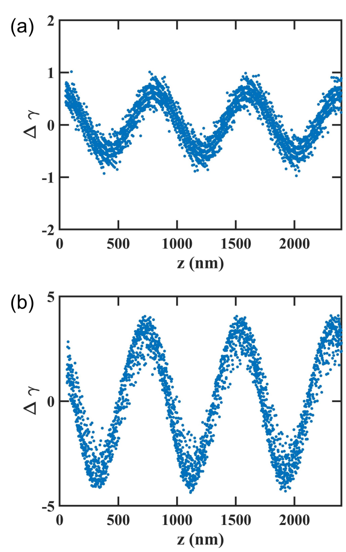

Figure 4: Modulation amplitude of different laser-electron interction at the same laser pulse energy 50 µJ (a): Gaussian beam (b): BG_{01} beam.

Figure 4 shows the phase space of the electron beam at the exit of the undulator for laser modulation. where $\Delta\gamma = \gamma - \gamma_0$ is the energy deviation relative to initial beam average energy. The electron beam phase space obtains sinusoidal shape energy modulation in the process of energy exchange with the laser light field. With the same laser pluse energy $E = 50$ µJ, the energy modulation amplitude of the electron beam is $\Delta\gamma < 1$ under the modulation of the Gaussian laser electron interaction, but the energy modulation amplitude is $\Delta\gamma \approx 5$ of the BG_{01} laser electron interaction, which means that the energy modulation amplitude can be improved by about five times.

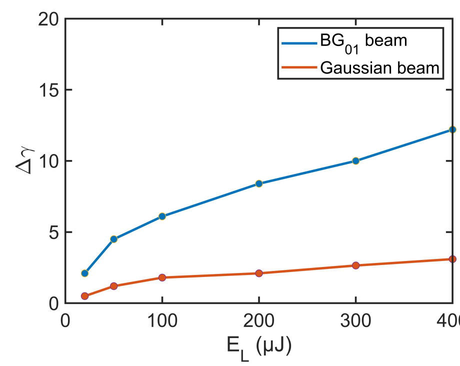

Figure 5: Variation of energy modulation amplitude with differant laser single pluse energy.

In order to further scrutinize the extent of laser power reduction after the introduction of BG_{01} beam, we have conducted simulations to get the modulation amplitude under various single pulse energy of the two lasers. The maximal modulation amplitude is shown in Fig. 5. One can find that, with the same seed laser energy, a larger modulation amplitude can be obtained by BG-electron interaction. The energy modulation amplitude by using pulse energy $E_L = 50$ µJ of BG_{01} beam monopulse is larger than using the $E_L = 400$ µJ of Gaussian laser. This shows that if the same modulation amplitude is achieved using a BG_{01} beam, the laser power can be effectively reduced by an order of magnitude during the actual modulation process.

CONCLUSION

In this paper, we proposed and analyzed numerically a new laser electron interactaction scheme that employs a vortex beam modulated within a helical undulator. By matching the ring width of the vortex beam and the transverse trajectory of the electron beam, the electron beam can obtain a higher energy modulation amplitude. The simulation results prove that this modulation method can effectively reduce the requirement for external laser power. This is of great significance for the development of high repetition frequency seed FEL and other coherent light sources.

ACKNOWLEDGEMENTS

This work is supported by the National Natural Science Foundation of China (NSFC) under Grant No. 12305158 and the Youth Innovation Promotion Association (CAS).

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPG72

REFERENCES

[1] G. Stupakov, "Using the beam-echo effect for generation of short-wavelength radiation," *Phys. Rev. Lett.*, vol. 102, p. 074 801, 7 2009. doi:10.1103/PhysRevLett.102.074801

[2] P. Ungelenk *et al.*, "Continuously tunable narrowband pulses in the thz gap from laser-modulated electron bunches in a storage ring," *Phys. Rev. Accel. Beams*, vol. 20, p. 020 706, 2 2017. doi:10.1103/PhysRevAccelBeams.20.020706

[3] K. Mecseki *et al.*, "High average power 88 w opcpa system for high-repetition-rate experiments at the lcls x-ray free-electron laser," *Optics letters*, vol. 44, no. 5, pp. 1257–1260, 2019.

[4] C.-Y. Tsai, "Theoretical formulation of multiturn collective dynamics in a laser cavity modulator with comparison to robinson and high-gain free-electron laser instability," *Phys. Rev. Accel. Beams*, vol. 25, p. 064 401, 6 2022. doi:10.1103/PhysRevAccelBeams.25.064401

[5] J. Yan *et al.*, "Self-amplification of coherent energy modulation in seeded free-electron lasers," *Phys. Rev. Lett.*, vol. 126, p. 084 801, 8 2021. doi:10.1103/PhysRevLett.126.084801

[6] Q. Zhou *et al.*, "Generation of perfect vortex beams by dielectric geometric metasurface for visible light," *Laser & Photonics Reviews*, vol. 15, no. 12, p. 2 100 390, 2021. https://doi.org/10.1002/lpor.202100390