THE ORBITAL ANGULAR MOMENTUM LIGHT GENERATED VIA FEL AT NLCTA

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Abstract

A scheme to create coherent light with orbital angular momentum (OAM) using Free Electron Laser (FEL) at Next Linear Collider Test Facility (NLCTA) is proposed. A 785 nm light co-propagating with relativistic un-modulated electron beam is fed through a helical undulator tuned to the second harmonic of the laser, which helically modulates it in energy. The energy modulation is transformed into helical density modulation by propagating through a longitudinally dispersive section, such as a chicane. Finally the helical density 3-D modulated beam is sent through a second undulator resonant at micro-bunching wavelength, causing the electron beam to radiate OAM light. Second harmonic helical undulator, and planar radiator need to be constructed for NLCTA conditions as they already have an optimized chicane for density modulation. According to simulations generated by Mathematica and Genesis 1.3, a 4 period long pre-buncher followed by a 100 period long undulator will be enough to create 0.8 GW 795 nm OAM light with an insignificant fundamental mode using the electron beam generated at NLCTA.

INTRODUCTION AND THEORY

Besides polarization, light can also carry an azimuthal component of momentum, which describes the phase evolution about the propagating axis; the OAM component $(l\hbar.)$ Some of the uses of OAM light are sub-diffraction limit spectroscopy, optical pump schemes, and potential future experiments in next generation light source research [1-8]. The traditional means of creating OAM light by introducing optical elements along the path of the laser fails when hard X-rays and high peak power light are concerned. We propose to utilize a scheme described in [9,10] to create high peak intensity OAM mode at NLCTA facility as a proof of principle experiment. The electron beam co-propagating with 795 nm light transverses a helical undulator resonant at the 2nd harmonic of the light, modulating the electron beam helically in energy space. A chicane changes the energy modulation to density modulation. The density modulated beam passes through a final radiator undulator tuned to the fundamental, but due to the helical density modulation it produces OAM light at the fundamental wavelength as opposed to the familiar simple Gaussian mode. Table 1 depicts the parameters for electron beam and laser at NLCTA.

Table 1: Electron Beam and Laser Parameters

Parameter	**Value**
Electron Energy (γ)	230
Energy Spread (σ_γ)	0.01%
Peak Current	1 kA
Normal Emittance (ε_{nx})	2 mm-mrad
Electron Beam rms size (σ_x)	0.1 mm
Laser wavelength (λ_b)	795 nm
Laser waist size (w_0)	189 μm
Input Laser Power	1 MW
Output Laser Power	0.8 GW

The analytical expression for energy modulation after a helical undulator is [10]:

$$\eta = \eta_0 \pm \mathrm{a}(r)\cos(\mathrm{k_b s_0} \mp \phi) \tag{1}$$

$$\mathrm{a}(r) = \frac{eK_h^2 L_m r}{\gamma^3 mc^2 k_w w_0^3}\sqrt{\frac{2P\mu_0 c}{\pi}}e^{-r^2/w_0^2}$$

where $\eta = (\gamma - \gamma_0)/\gamma_0$, the energy deviation from electron resonant energy, $K_h = eB/mck_w$ is rms undulator constant, $k_w = 2\pi/\lambda_w$, and L_m is the modulator length $L_m = k_b w_0^2/2 = 14$ cm. This followed by a chicane optimized for micro-bunching of $R_{56} = 316$ μm, where σ_γ is the energy spread. This changes the energy modulation to a density modulation as shown in Eq. 2:

$$\varphi = \varphi_0 + k_b \mathrm{R}_{56}\eta \tag{2}$$

After we use the helical undulator to energy-modulate the beam we want to get rid of the initial co-propagating laser so we put a beam dump to ensure that it doesn't enter the next phase. The reason for that is because fundamental mode will grow a lot faster through the radiator then the OAM mode, and if it's not subdued initially will take over. M. Xie in [11] derives an analytic formula which can be used to calculate the gain length of the azimuthal mode in a given system as a function of diffraction parameter (η_d), longitudinal velocity spread due to energy spread (η_γ), and longitudinal velocity spread due to emittance (η_ε) and the detuning. For NLCTA the calculated gain length of the fundamental is 1.36 L_{1d}=17.7cm at the detuning that minimizes the gain length. We solved this expression for the *l*=1 mode, and found that the OAM gain length is 2.27 L_{1d}=29.5 cm, which is long compared to the fundamental. It is therefore important to minimize amplification of the fundamental mode, both by enforcing that the upstream modulating seed laser does not get amplified in the radiator, and by ensuring that the helical bunching factor is much larger than the bunch factor due to shot noise (which also seeds the fundamental mode). Ensuring that polarization of radiator is orthogonal to the polarization of the upstream modulating seed guarantees lack of amplification of the feed laser. Otherwise the seed can also be minimized by blocking it with a beam dump, or passing it through an aperture. When designing the pre-buncher we also want to make sure that we do not saturate in power too soon, so our equivalent bunching factor power is 20 times less then saturation power. In setting up the simulation we chose our OAM bunching coefficient to be around 5%, which creates a fundamental bunching of about 0.03%. This overestimates the contribution of shot noise in our simulation, and means that experimental fundamental mode will be even more insignificant then predicted, because theoretically we expect shot noise bunching to be ~10^{-5} because $b_{sn} = \frac{1}{3\sqrt{N_\lambda}}$ where $N_\lambda = \frac{ec}{I}\frac{\sqrt{2\pi\rho}}{\lambda}$ is the number of electrons in a coherence length from a 1D model.

SIMULATION

Using Mathematica we simulate the initial un-modulated beam, as an array of particles which randomly occupy a specific phase space dictated by beam size, normalized emittance, energy, and energy spread of the beam. Using algorithms described before (See Eq. 1 & Eq. 2) we modulate the beam to include micro-bunching in energy to simulate the helical undulator effect, and then modulate it again with an optimal R_{56} to simulate a chicane modulation that turns energy into density modulation. We plot energy spread as a function of phase in Figure 1. The modulated particles are put into Genesis 1.3 through a final radiating undulator generating radiation intensity and phase (Figure 2), power radiated (Figure 3), and fundamental bunching (Figure 4). The radiator is detuned by 2.5% to facilitate OAM bunching growth. In Table 2 are the optimal parameters for the two undulators, where H stands for helical pre-buncher, and R stands for planar radiator. The power increases to 0.8 GW at saturation at 3 m of radiator length, while the fundamental bunching stays around 1%. This shows that most of light generated is OAM.

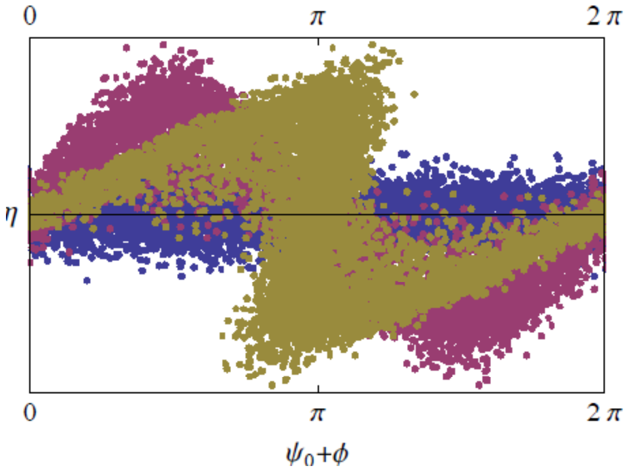

Figure 1: Energy spread against phase: (blue) un-modulated; (red) helical energy modulated; and (yellow) chicane modulated.

Table 2: Helical Pre-buncher and Planar Radiator Parameters

Parameter	Value
H Undulator Constant (K_h)	2
H Undulator Period (λ_h)	3.39 cm
H Number of Periods	4
H Permanent Dipole Strength	1.4 T
R Undulator Constant (K_r)	1.32
R Undulator Period (λ_r)	2.9 cm
R Number of Periods	100
R Permanent Dipole Strength	3.2 T

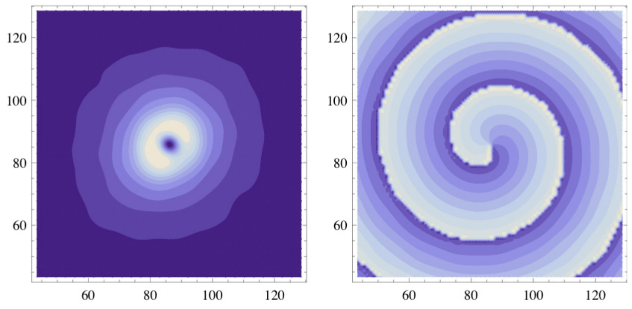

Figure 2: Far field intensity (left) and phase (right) after 2.5 m of radiator.

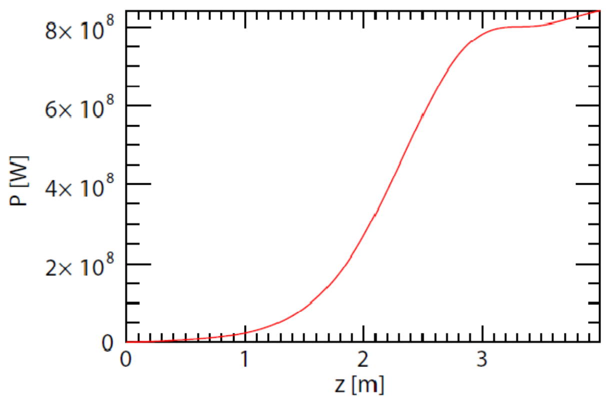

Figure 3: Power as a function of radiator distance.

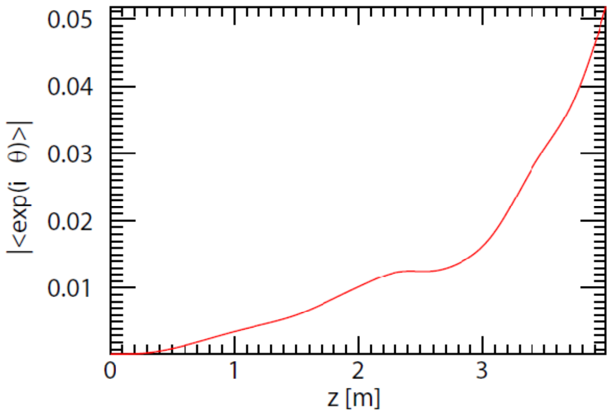

Figure 4: Fundamental bunching vs. Radiator distance.

Table 3: Calculated Important Quantities

Parameter	**Value**
R Undulator Parameter(ρ)	0.01
1-D Gain Length (Lg)	13 cm
Saturation Power	1.6 GW
Diffraction Parameter (η_d)	0.81
Longitudinal velocity spread due to energy spread (η_γ)	0.005
Longitudinal velocity spread due to emittance (η_ε)	0.015

CONCLUDING REMARKS

Analytic and computer simulations have been done to show that high power OAM modes can be produced via FEL interaction. Applying these results experimentally is the next step, which we propose to do in NLCTA, because they have (a) a high energy electron beam with a sub micron laser wavelength, which means high K with large undulator periods of 3-4 cm; so magnets will be relatively easy to manufacture; (b) availability of a chicane which is already optimized for their facility parameters; (c) simulations show a 0.8 GW of OAM power produced.

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REFERENCES

[1] E. Hemsing, P. Musumeci, S. Reiche, R. Tikhoplav, A. Marinelli, J.B. Rosenzweig, A. Gover, Phys Rev. Lett. 102, 174801 (2009).

[2] G. Gibson, J. Couritial, M. Padgett, M. Vasnetsov, V. Pas'ko, S. Barnett, and S. Franke-Arnold, Opt Express 12, 5448(2004)

[3] E. Yao, S. Franke-Arnold, J. Courtial, M.J. Padgett, and S. M. Barnett, Opt Express 14, 13089 (2006)

[4] M. F. Anderson, C. Ryu, P.Clade, V. Natarajan, A. Vaziri, K. Helmerson, and W.D. Phillips, Phys. Rev. Lett. 97, 170406 (2006)

[5] A. Alexandrescu, D. Cojoc, and E. DiFabrizio, Phys. Rev. Lett. 96, 243001 (2006)

[6] B. Jack, J. Leach, J. Romero, S. Franke-Arnold, M. Ritsch-Marte, S. M. Barnett, and M. J. Padgett, Phys. Rev. Lett. 103, 083602 (2009)

[7] P Török and P Munro, Opt Express 12, 3605 (2004)

[8] J. W. R. Tabosa and D. V. Petrov, Phys. Rev. Lett. 83, 4967 (1999)

[9] EmmaP., AkreR., ArthurJ., BiontaR., BostedtC., BozekJ, BrachmannA., BucksbaumP., CoffeeR., D. J., et al. Nat Photon 4, 641 (2010); http://dx.doi.org/10.1038/nphoton.2010.176

[10] E. Hemsing, A. Marinelli, J. B. Rosenzweig, Phys. Rev. Lett. (to be published)

[11] M. Xie, Nuclear Instruments and Methods in Physics Research A 445 (2000) 59-66