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COHERENT RADIATION FROM INVERSE COMPTON SCATTERING SOURCES BY MEANS OF PARTICLE TRAPPING*

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Abstract

Inverse Compton scattering (ICS) sources are one of the promising compact tools to generate short wavelength radiation from electron beams based on the relativistic Doppler effect. Nonetheless, these sources suffer from a few shortcomings such as incoherent radiation and low-efficiency in radiation generation. This contribution presents a novel scheme based on the scattering of an optical beam from a confined/trapped electron beam inside an optical cavity. Inverse-Compton scattering off both free and confined electrons are simulated using a full-wave solution of first-principle equations based on FDTD/PIC in the co-moving frame of electron beams. It is shown that the strong space-charge effect in low-energies is the main obstacle in acquiring coherent gain through the ICS mechanism. Subsequently, it is shown that by confining the electron beam to the cavity nodes, the space-charge effect is compensated, and additionally, the ultrahigh charge density enables high FEL-gain at confinement spots, thereby augmenting the coherence of the output radiation and concurrently increasing the source efficiency by three orders of magnitude.

INTRODUCTION

The advent of x-ray free-electron lasers (FELs) led to breakthrough progress by increasing the x-ray source peak brightness by up to ten orders of magnitude when compared to synchrotron radiation facilities [1, 2]. This remarkable progress revolutionized light source development specifically in the x-ray domain, and enabled studies with ultrashort time resolutions and/or ultra-high spectral resolution [3]. This breakthrough is emphasized by calling FELs fourth generation light sources [4]. After the successful implementation of the first soft x-ray FEL, FLASH at DESY in 2005 [5], and the first hard x-ray FEL LCLS at SLAC in 2010 [6], implementation of various x-ray FEL facilities have been triggered. FEL facilities in South Korea [7], Japan [8] and Italy [9] are now successfully operating for many years. The 3.4 km long facility European-XFEL started operation initially at a wavelength of 1.4 nm (900 eV) in 2017.

Despite the unprecedented possibilities offered by FEL technology, the requirement for building a large facility to produce the output x-ray beamline considerably hampers the research progress in this field. These giant lasers are not portable, operate with high energy consumption, and moreover their upgrade usually demands substantial effort and longtime shutdown of the facility. These challenges have motivated extensive research efforts around the world to realize the so-called "table-top" x-ray sources that offer x-ray generation with the same efficiency but in a compact setup. To this end, different techniques such as laser-plasma wakefield acceleration (LPWA), THz acceleration, dielectric-laser acceleration (DLA), cryogenic undulators, optical undulators and nano-undulators are being examined in various institutes. For a more detailed review on compact x-ray source research, the reader is referred to [10]. Here, we present a new scheme for realizing a compact x-ray source which is based on confining electron beams to weak field regions inside an optical/electromagnetic cavity. Hence, we name the proposed device as confined/trapped electron laser compared to the conventional free electron laser.

The theory of free electron laser based on static undulators was pioneered by R. Bonifacio and L. Pellegrini in 1984 [2]. Four years after the proposal of FEL, the theory of optical undulators was developed by Gallardo et al. [11]. Nonetheless, there exists no operational FEL facility today based on optical or electromagnetic undulators. This contribution, through full-wave simulation of optical undulator radiation using FDTD/PIC algorithm in the Lorentz-boosted framework, firstly demonstrates that the strong space-charge forces in the low-energy electron beams preclude the coherent gain in the radiation inside an optical undulator. Secondly, it is shown that by adding the fields of an optical cavity that transversally confines the electron beam to field nodes, the coherent gain can be triggered.

NUMERICAL RESULTS

Figure 1 schematically illustrates the proposed confined electron laser setup compared with the conventional FEL with optical undulator mechanism. The device consists in an electron beam wiggled by a counter propagating laser as in an optical undulator or inverse Compton scattering setup. However, the interaction is performed inside an optical cavity which imposes ponderomotive (gradient) forces to the electrons. These forces trigger three interdependent phenomena in the electron beam propagation and radiation: (i) The gradient forces suppress the increase in beam transverse size that consequently minimizes the *effective* beam emittance, (ii) The ponderomotive forces prevent the transverse expansion of the beam size due to Coulomb forces, and (iii) the single e-beam with low charge density is divided into multiple micro-beams with dramatically higher charge densities that have stronger potentials for micro-bunching and lasing.

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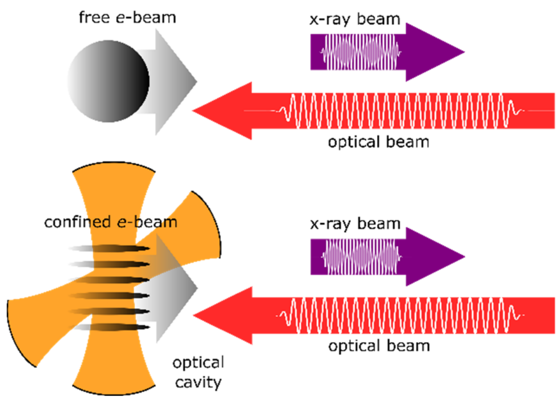

Figure 1: Schematic illustration of optical undulator with confined electrons compared to free electrons.

Table 1: Source Parameters

Parameter	Value
Current profile	Uniform
Bunch RMS size ($\sigma_x = \sigma_y$)	5 µm
Bunch length (σ_z)	20 µm
Bunch charge (Q)	0.64 pC
Bunch energy (E)	5.12 MeV
Bunch current (I)	9.6 A
Longitudinal momentum spread ($\sigma_{\gamma\beta_z}$)	2.5×10^{-3}
Normalized emittance (ϵ_n)	50 nm-rad
Laser wavelength (λ_0)	10 µm
Laser strength parameter (a_0)	1.0
Pulse duration (cT)	18 mm
Laser pulse type	Flat-top
Radiation wavelength (λ_x)	37.6 nm
Cavity wavelength (λ_c)	11.8 µm
Cavity beam size ($w_{0x} \times w_{0y}$)	7.4×0.1 mm^2
Cavity beam strength parameter (a_{0c})	0.07
Beam focal position ($c\delta t$)	8.4 mm

We use the code MITHRA 2.0 to simulate the interaction through a Finite-Difference Time-Domain / Particle-in-Cell (FDTD/PIC) algorithm [12]. The interaction parameters chosen based on the state-of-the-art electron gun and laser technology, are tabulated in Table 1. The results of the simulation are shown in Fig. 2, where the radiated power and temporal field magnitude in front of the bunch are depicted in terms of the propagation length. Considering the simulation results for laser beam scattered off a free electron beam with and without space-charge effect, it is observed that the Coulomb repulsion between the electrons in the low energy (5 MeV) beam completely hampers the coherent gain. In other words, the space-charge effect that is typically neglected in FEL operation due to ultra-relativistic energies is no more negligible.

The results for the same simulation but with the cavity fields show an outstanding enhancement in the radiation. It is observed that the radiation begins with an initial incoherent radiation, originated from the shot noise in the bunch electron distribution, proceeds with a gain regime in the radiation and ultimately the radiated power is saturated. This is analogous to the conventional FEL operation.

In Fig. 3, the field and bunch profile as well as the radiated power profile are visualized at the maximum radiation instant. The occurrence of microbunching is clearly observed in the confined microbeams, whereas the free beam does not show any microbunching. Furthermore, the field profile of the radiation indicates forward radiation as strong as the backward coherent radiation, which is another confirmation of a coherent lasing of the confined electron beam inside the cavity. The radiated power profile is different from a conventional free electron laser, where a single beam is created. In the confined electron laser concept, there exist several microbeams that radiate simultaneously in phase parallel to each other. The radiation profile of these microbeams can be understood by referring to the theory of array antennas, where a main lobe as well as several side lobes exist in the radiation pattern. Such a profile is also observed in the radiation of the confined electron beam.

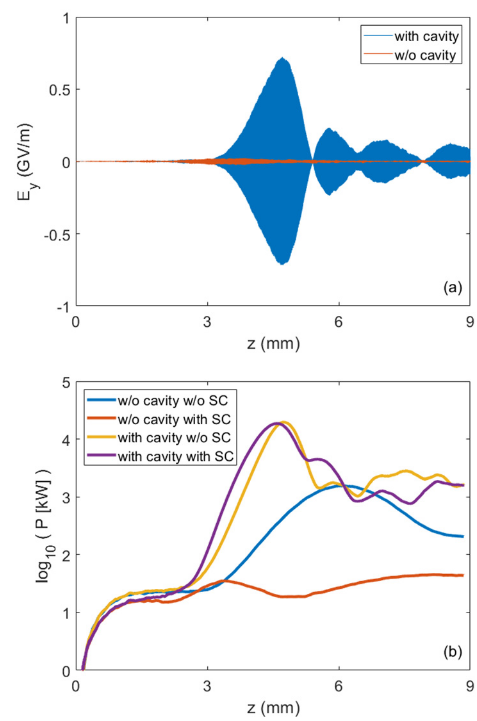

Figure 2: (a) temporal signature of the radiated field value sampled on-axis in front of the bunch for trapped and free electrons, and (b) radiated power on logarithmic scale versus undulator length for free and trapped electrons with and without considering space-charge effect.

CONCLUSION

This contribution aimed at introducing a new laser device, named as confined electron laser, that enables a compact coherent x-ray sources. The device is based on inverse Compton scattering off low-energy electrons transversely confined inside fields of an optical cavity. In the fields of an optical cavity, there exist transverse gradient forces that push the particles towards regions with weak field values.

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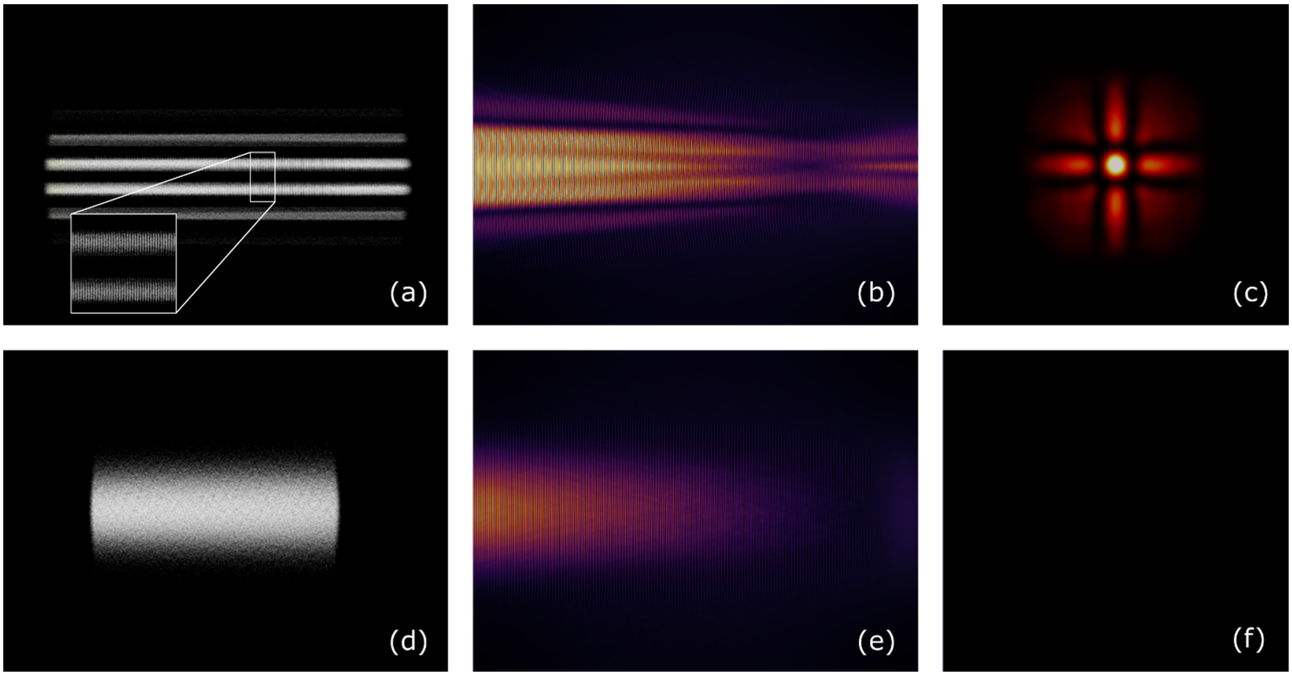

Figure 3: Visualization of the simulation results at the instant of maximum radiated power: (a) bunch profile, (b) field profile, and (c) beam power profile in front of the bunch for confined electrons, and (d) bunch profile, (e) field profile, and (f) beam power profile in front of the bunch for free electrons.

These forces lock, or focus, the electrons to the cavity nodes and minimize the beam divergence due to transverse energy spread or Coulomb repulsion. It is theoretically demonstrated that the microbeams produced by this scheme offer the possibility of achieving fast coherent gain before bunch expansion. As a result, using an optimal design of the cavity parameters compact x-ray sources can be devised that enable efficiencies close to the existing x-ray free-electron lasers.

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REFERENCES

[1] A. M. Kondratenko and E. L. Saldin, “Generating of coherent radiation by a relativistic electron beam in an ondulator”, *Part. Accel.*, vol. 10, pp. 207–216, 1980.

[2] R. Bonifacio, C. Pellegrini, and L. M. Narducci, “Collective instabilities and high-gain regime free electron laser”, *AIP Conf. Proc.*, vol. 118, pp. 236–259, 1984. doi:10.1063/1.34640

[3] K. J. Gaffney and H. N. Chapman, “Imaging atomic structure and dynamics with ultrafast X-ray scattering”, *Science,* vol. 316, pp. 1444–1448, 2007. doi:10.1126/science.1135923

[4] B. W. J. McNeil and N. R. Thompson, “X-ray free-electron lasers”, *Nat. Photonics*, vol. 4, pp. 814–821, 2010. doi:10.1038/nphoton.2010.239

[5] W. Ackermann *et al.*, “Operation of a free-electron laser from the extreme ultraviolet to the water window”, *Nat. Photonics*, vol. 1, pp. 336-342, 2007. doi:10.1038/nphoton.2007.76

[6] P. Emma *et al.*, “First lasing and operation of an ångstrom-wavelength free-electron laser”, *Nat. Photonics*, vol. 4, pp. 641–647, 2010. doi:10.1038/nphoton.2010.176

[7] H.-S. Kang *et al.*, “Hard X-ray free-electron laser with femtosecond-scale timing jitter”, *Nat. Photonics*, vol. 11, pp. 708–713, 2017. doi:10.1038/s41566-017-0029-8

[8] T. Ishikawa *et al.*, “A compact X-ray free-electron laser emitting in the sub-ångström region”, *Nat. Photonics*, vol. 6, pp. 540–544, 2012. doi:10.1038/nphoton.2012.141

[9] E. Allaria *et al.*, “Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultraviolet”, *Nat. Photonics*, vol. 6, p. 699, 2012. doi:10.1038/nphoton.2012.233

[10] A. Fallahi, N. Kuster, and L. Novotny, “Transverse Confinement of Electron Beams in a 2D Optical Lattice for Compact Coherent X-Ray Sources”. arXiv:2104.11586

[11] J. C. Gallardo, R. C. Fernow, R. Palmer, and C. Pellegrini, “Theory of a free-electron laser with a gaussian optical undulator”, *IEEE J. Quantum Electron.*, vol. 24, pp. 1557-1566, 1988. doi:10.1109/3.7085

[12] A. Alba, A. Adelmann, and A. Fallahi, “OPAL-MITHRA: Self-consistent Software for Start-to-End Simulation of Undulator-based Facilities”, in *Proc. of the 33rd Int. Vacuum Nanoelectronics Conf. (IVNC'20)*, Lyon, France, Jul. 2020. doi:10.1109/IVNC49440.2020.9203404