NUMERICAL STUDIES ON TUNABLE COHERENT RADIATIONS WITH A LASER-PLASMA ACCELERATOR*

J.J. Kim, M.S. Kim, I.H. Nam*, H. Suk†, GIST, Gwangju, Republic of Korea, SLAC National
M.S. Hur, UNIST, Ulsan, Republic of Korea

Abstract

Generation of tunable coherent radiation is numerically investigated via the two-dimensional particle-in-cell (2D-PIC) code developed by UNIST [1] and SIMPLEX developed by Spring-8. The electron beams can be produced by the laser-driven wakefield acceleration technique. The electron beam energy can be easily adjusted between 450 MeV and 800 MeV with a tapered density plasma on the order of 1×10^{18} cm^{-3} while the driving laser power is fixed, and the high-energy electron beams can be sent through the undulator arrays for the coherent light emission. The energy-controllable electron bunches can provide an opportunity to control the radiation wavelength with the fixed gap undulators. For the tapered density profile, a capillary cell with two gas inlets can be used. In this paper, we show some simulation and numerical research results regarding these issues, which reveal the possibility for a tunable light source in the soft X-ray regime.

INTRODUCTION

Since the laser wakefield accelerator (LWFA) concept was proposed by Tajima and Dawson in 1979 [2], an enormous number of achievements have been performed to aim at the generation of the beam energy in GeV scale with table-top accelerator. However, the maximum beam energy by LWFA is still limited by the dephasing of accelerated electrons in the wakefield, the laser power depletion, and the diffraction of the laser [3], and even there is no flexibility on the accelerated electron beam energy with uniform plasma density source. Here, the laser diffraction and depletion can be solved by using the parabolic guiding density profile provided by the discharge capillary plasma source [4] and high-power laser. In case of the dephasing effect, the one idea to overcome is using the up-tapered plasma density profile [5]. Under the up-tapered density distribution, the phase changing point between acceleration and deceleration moves forward due to the cavity length shortening, so that the accelerated electrons will stay longer in the acceleration phase of the wakefield. Furthermore, the concept of the tapered-density plasma provides the chance to control electron beam energy freely.

In this paper, we particularly consider the feasibility of the generating tunable coherent radiation based on the energy-controllable electron beams from the density-tapered plasma source.

SIMULATION RESULTS

Electron Beam Generation

2D-PIC code named as cplPIC is used to simulate the electron beam generation with the energy tunability. In the simulations, the laser wavelength is $\lambda_0 = 800$ nm, and the peak power is 30 TW with 30 μm spot diameter and 59 fs pulse duration. The fs high-power laser is focused in the fully ionized plasma with the density $n_\mathrm{i} = 2 \times 10^{18}\ cm^{-3}$ and then electrons are trapped by the density transition. After accelerated electrons are trapped, they experience density tapering as shown in Fig. 1. The final plasma density varies from $n_\mathrm{f} = 7 \times 10^{17}$ to $n_\mathrm{f} = 2.4 \times 10^{18}\ cm^{-3}$ corresponding to $0.6n_0$ and $2n_\mathrm{i}$. Those parameters are arranged in table. 1.

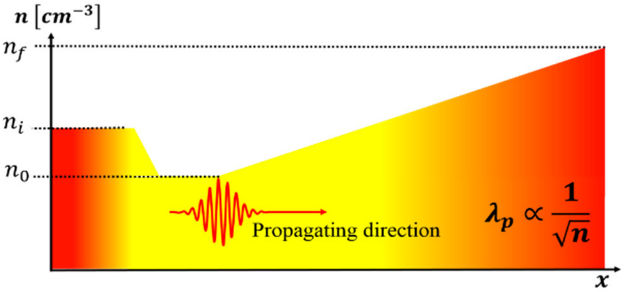

Figure 1: Plasma density profile for simulations.

Table 1: PIC Parameters

Parameter	Value	Unit
Normalized laser intensity	3	a_0
Pulse duration τ	~ 59	fs
Beam diameter w_0	~ 30	μm
Initial plasma density n_i	2	10^{18}cm^{-3}
Min. plasma density n_0	1.2	10^{18}cm^{-3}
Max. plasma density n_f	0.7~2.4	10^{18}cm^{-3}

The energy spectra of the generated electron beams are given in Fig. 2. The center energies for negative-, non-, and positive-tapered are 460, 625, and 787 MeV. For all cases, the accelerated electron beams have the value of around 1.6 pC of charge, smaller than 2 μm for the bunch length, around 0.22 πmm · mrad of the normalized transverse emittance. The energy spread is, particularly, remained around 1 % (FWHM) as shown in Fig. 2. Therefore, it is

---

† hysuk@gist.ac.kr
* Present address : Accelerator Laboratory, Menlo Park, CA, USA

possible to change only the main electron energy for tunable radiation, without any severe degradation of the beam quality by using tapered density profile.

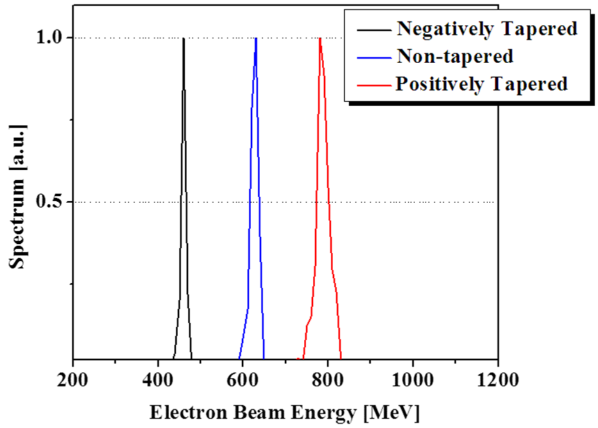

Figure 2: The energy spectra of electron beams for negatively tapered, non-tapered, and up-tapered cases.

Accelerated beam quality is much higher than the typical self-trapped case so that it is appropriate to apply the coherent light emission. We accelerated the electrons along only 6-mm-long-plasma which is much shorter than the dephasing length to focus on the radiation in the soft X-ray regime. The energies will be around 1 GeV or higher after full acceleration according to the energy gain equation $\Delta E[\mathrm{GeV}] \simeq 1.7(P_0[\mathrm{TW}]/100)^{1/3}(10^{18}/n[cm^{-3}])^{2/3}$ [6], where P_0 is the laser peak power and n is the plasma density.

Tunable Coherent Radiation

The used parameters of the energy-controllable electron beam for tunable coherent light emission are as shown in table. 2.

Table 2: Electron Beam Parameters

Parameter	Value	Unit
Center energy	450~800	MeV
Energy spread	0.4 ~1.2	%
RMS transverse emittance	~ 0.22	π mm · mrad
Bunch duration	< 5	fs
Transverse size	< 4	µm
Peak current	~ 1	kA

The beam parameters are used in SIMPLEX to see the tunable coherent light emission through the undulator arrays with the dimensionless undulator strength parameter K=0.67. The simulated coherent radiation spectra on the propagating axis are illustrated in Fig. 3. The on-axis radiation wavelengths are 4.5, 2.4, and 1.6 nm corresponding to the electron beam energies of 460, 625, and 787 MeV, relatively, which are given by $\lambda_r = (\lambda_u/2\gamma^2)(1+K^2/2)$ with the electron's relativistic Lorentz factor γ [7].

The radiation powers along the beam propagating direction are shown in Fig. 4 which finally reach 10, 8, 6 MW by the electron beams of 460, 625, and 787 MeV. Also the peak brilliances are on the order of 1×10^{27} with the unit of photons/sec/mm^2/mrad^2/0.1%B.W.

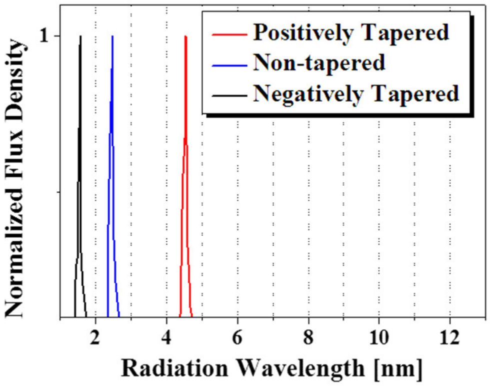

Figure 3: The coherent radiation spectra from fixed gap undulator using the energy controllable electron beams.

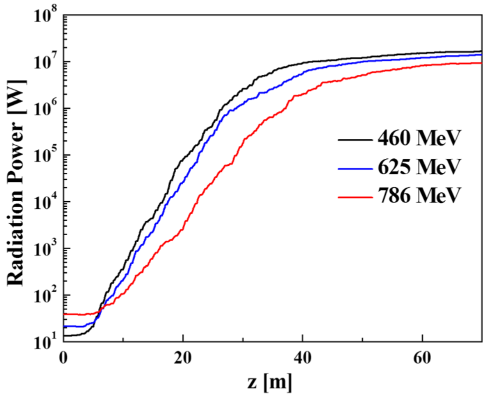

Figure 4: Radiation power along the beam propagating direction.

SUMMARY

In summary, it is shown that the feasibility of the energy-controllable electron beam generation via 2D-PIC simulation with density-tapered plasma, while the used laser power is constant. The tapered density profile experimentally can be realized by employing the capillary with two different inlet sizes at the same gas pressure or with two inlets at different gas pressure. Accordingly, the opportunity to generate the tunable coherent light emission from undulator arrays in soft X-ray range using fixed gap undulators, is given, and the coherent light emitting system based on the energy-controllable electron beam is simulated by the SIMPLEX code.

REFERENCES

[1] M. S. Hur, and H. Suk, "Numerical study of 1.1 GeV electron acceleration over a-few-millimeter-long plasma with a tapered density", *Phys. Plasmas*, Vol. 18, no. 3, p. 033102, Mar. 2011.

[2] T. Tajima, and J. M. Dawson, "Laser Electron Accelerator", *Phys. Rev. Lett.*, Vol. 43, no. 4, pp. 267-270, July 1979.

[3] E. Esarey, C. B. Schroeder, and W. P. Leemans, "Physics of laser-driven plasma-based electron accelerators", *Rev. Mod. Phys.*, Vol. 81, no. 3, pp. 1229-1285, Aug. 2009.

[4] N. A. Bobrova et al., "Simulation of a hydrogen-filled capillary discharge waveguide", *Phys. Rev. E*, Vol. 65, no. 1, p. 016407, Dec. 2001.

[5] P. Sprangle et al, "GeV acceleration in tapered plasma channels", *Phys. Plasmas*, Vol. 9, no. 5, pp. 2364-2370, May 2002.

[6] W. Lu et al., "Generating multi-GeV electron bunches using single stage laser wakefield acceleration in a 3D nonlinear regime", *Phys. Rev. ST-AB*, Vol. 10, no. 6, p. 061301, June 2007.

[7] Z. Huang, and K.-J. Kim, "Review of x-ray free-electron laser theory", *Phys. Rev. ST-AB*, Vol. 10, no. 3, p. 034801, Mar. 2007.