As to the electron bunch parameter and quality, the laser-driven plasma accelerator can generate a high quality bunch [19]. The FEL gain process starts only on the flattop part of the laser as in Fig. 2(d), and no gain on the rising edge. With the parameters in Fig. 3, the FEL Pierce parameter is about $\rho \sim 0.0017$ [14], which characterizes the lasing efficiency $P_{\rm FEL} \approx \rho(\gamma m_e c^2/e)I$ [14]. The GENESIS simulation gives a saturation power at the end of exponential growth of about $P_{\rm sat} \approx 120$ MW. The simulated FEL power for no taper case as the blue solid curve in Fig. 3 is consistent with the analytical estimate with 3-D gain length of $L_G = 0.44$ mm [14]. The FEL power for the tapered case (the red curve) is over 1 GW, about one order higher than that for the no tapered case. The wavelength spectrum shown in Fig. 3(b) represents a relative narrow bandwidth radiation. Fitting to a Gaussian envelop gives a FWHM relative bandwidth of 4.4×10^{-3} for a flattop electron bunch of about 100 fs duration. The far field transverse image is shown in Fig. 3(c) which is very close to a fundamental Gaussian mode with $M^2 \approx 1.03$ and transverse divergence $\sigma_{x'} \approx \sigma_{y'} \approx 86$ μrad and waist size of $w_0 = 4.9$ μm. In reality, the optical undulator is a Gaussian mode $E(x) = E_0 \exp[-x^2/(4\sigma_{L,x}^2)]$ with E_0 the peak electric field and $\sigma_{L,x}$ the laser intensity rms x-size. The Gaussian distribution in the x-direction is similar to the transverse-gradient undulator [20], which can be used to compensate the energy spread of electron bunch if we inject the electron bunch with an x-offset from the laser center. We con-

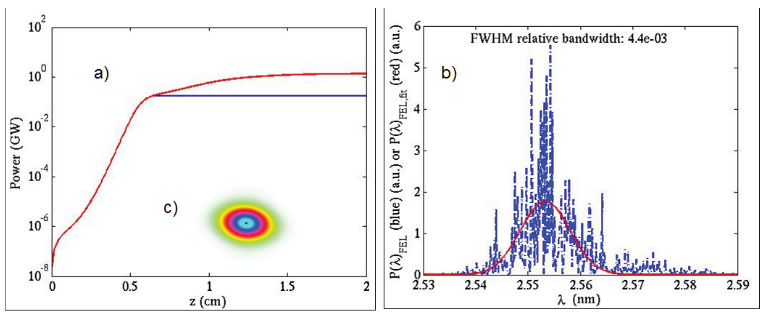

Fig. 3. (a) Radiation power without taper (blue curve) and with taper (red curve); (the length of taper L=2.3 cm, a = 0.4); (b) the spectrum; and c) Far field image of the X-ray pulse. The simulation parameters are: electron bunch central energy $\gamma = 80$, energy spread $\sigma_\gamma = 0.1$, normalized emittance $\varepsilon_N = 0.2$ π mm mrad, peak current $I = 3$ kA, beam transverse radius 5 μm, RMS $K = 1.5$, and the undulator period $\lambda_u = 10$ μm. There is no focusing magnet.

clude on the discussion of the peak brightness, defined as $B \equiv \dot{N}_{ph}/(4\pi^2\sigma_T^2\sigma_{T'}^2 d\omega/\omega)$ where T stands for x or y, *i.e.*, the transverse dimension, $\sigma_{T'}$ for the RMS opening angle, $d\omega/\omega$ the relative bandwidth, and $\dot{N}_{ph}$ the flux of FEL. The peak brightness of the FEL pulse in our scheme achieves 10^{30} photons/mm^2/mrad$^2/s/0.1\%$ bandwidth, which is 10 orders (*i.e.*, 10^{10} times) higher than the max theoretical brightness for the incoherent nonlinear Thompson Scattering [21] with only spontaneous radiation and no gain. Notice that, for undulator radiation the bandwidth of the central cone scales as $d\omega/\omega \sim 1/N_u$, and the RMS opening angle scales as $\sigma_{T'} = \sqrt{(1+K^2)/(2N_u)}/\gamma$, thus, the brightness of X-ray is proportional to N_u^2. Therefore, even if there is no FEL-type exponential growth, the X-ray source's brightness benefits largely from the lengthened interaction time. For a sufficient long optical undulator with number of periods $N_u > 10L_G/\lambda_u$, the interaction length can be 10-20 gain length, thus, with a high quality electron bunch, the high-gain Thompson Scattering FEL can be realized.

Acknowledgments

The work was supported by the US Department of Energy (DOE) under contract DE-AC02-76SF00515 and the US DOE Office of Science Early Career Research Program grant FWP-2013-SLAC-100164.

#199142 - $15.00 USD Received 8 Oct 2013; revised 22 Nov 2013; accepted 23 Nov 2013; published 17 Dec 2013