Seeded FEL Microbunching Experiments at the UCLA Neptune Laboratory

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Abstract. Seeded high-gain FELs, which can generate very powerful radiation pulses in a relatively compact undulator and simultaneously modulate the electron beam longitudinally on the seed wavelength, are important tools for the advanced accelerator development. A single-pass 0.5-9 THz FEL amplifier-buncher driven by a regular photoinjector is being built at the UCLA Neptune Laboratory. FEL interactions at 340 μm (1 THz) are considered for the first experiment, since time-resolved measurements of longitudinal current distribution of the bunched beam using the RF deflecting cavity are possible. A design of a 0.2-2.0 μm FEL using the same undulators is presented. In this case the FEL is driven by a high-peak current beam from the laser-plasma accelerator tunable in the 100-300 MeV range.

Keywords: free-electron laser, microbunching, THz radiation.
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INTRODUCTION

Seeded FEL/IFELs, based on resonant interaction between laser and electron beams in an undulator, can be used to produce high-output power radiation [1,2] or longitudinally modulate the electron beam on the seed radiation wavelength (microbunching) [3]. A seeded single-pass FEL amplifier allows for using a short, high peak current drive beam and reaching a very high FEL gain that can shorten the undulator length required for saturation. These schemes have great potential for radiation production in the extreme sides of the em spectrum: for the 1-10 THz and for the UV/soft X-ray spectral ranges where other sources of coherent radiation are scarce. However, very little is done on experimental testing of the ideas.

At UCLA we have launched an experimental program with the goal of developing a single-pass FEL amplifier-buncher seeded in the 100-680 μm (0.5-3 THz) range as well as the 0.2-2 μm range. The main objectives of the project are studying microbunching of the electron beam, that is directly related to electron-radiation coupling inside the undulator, and generation of megawatt power pulses tunable in the range of 0.5-9 THz. For the THz FEL experiments, the ~12 MeV Neptune S-band photoinjector will be used as a driver. However, the driver for a short wavelength FEL should operate at the 0.1-0.3 GeV energy range, where RF based linear accelerators become very large and expensive. An alternative approach is to use an advanced Laser Wakefield Accelerator (LWFA) as a small size driver for the UV/soft X-ray FELs [4]. Demonstration of a compact seeded FEL amplifier driven by a LWFA can become a key point in development of short-wavelength FELs due to high temporal and spatial coherence of radiation built up from the seed. It is important that using the same 40 fs, 800 nm laser pulses for driving the LWFA and for the seed production in the 0.2-2 μm range [5] provides synchronization between the electron and the radiation beams.

In this paper we describe the status of FEL program and also consider two seeded FEL schemes to be studied experimentally at the UCLA Neptune Laboratory. First, a 340 μm FEL-microbuncher, where a 1 kW seed is amplified to 300 kW peak power level resulting in picosecond modulation of the photoinjector beam. Second, an FEL driven by ~100 MeV electron beam generated by the LWFA, which is seeded at 1.4 μm. Both these experiments will be using undulators designed and built by STI Optronics for this program.

NEPTUNE UNDULATOR

The FEL undulator is a planar permanent magnet designed in two sections: a ~2-m long (60 full periods) and a ~1-m long (30 periods) undulator. Table 1 lists the operating parameters of the Neptune undulator designed and manufactured by STI Optronics (PI Steve Gottschalk). The 6th order parabolic pole shaping is used to achieve two-plane focusing and a symmetric round electron beam over the entire length of the undulator, which is important for seeded FELs. The undulators have a variable gap of 8-20 mm providing flexibility in choosing resonant conditions for both fundamental and harmonics of the seed wavelength. At present both magnets are assembled and characterized.

TABLE 1. Operating Parameters of the Neptune undulator.

Undulator Parameters	Values
Period	3.3 cm
Strength	K=2.506
Length	L~2 m (60 full periods) and L~1 m (30 full periods)
Peak Field	0.813 T
Gap	8-20 mm
Waveguide	ID=5 mm

An 8-14 MeV electron beam with a peak current up to 100 A produced by the Neptune photoinjector [6] is suitable for seeded THz microbunching experiments. Use of a tandem of the undulators separated by a drift space allows for covering the entire range of interest from 0.5 to 9 THz with a seed source tunable only in the 0.5-3 THz spectral window via the following mechanisms: 1) Frequency range 0.5-1.5 THz. Single-pass FEL amplification of ~ 1kW seed in a 2-m long undulator to 2-10 MW power level corresponding to a saturation power. 2) Frequency range 1.5-3.0 THz. Optical klystron scheme where the first undulator seeded at the 10-100 W level modulates the electron beam longitudinally, then the chicane transforms the energy modulation into a current modulation and the 1-m long undulator-radiator produces MW power pulses. 3) Frequency range 3-9 THz. High Gain Harmonic Generation (HGHG) scheme where a beam modulated at a seed frequency of 1-3 THz will be sent in the 1-m long undulator-radiator tuned to the 3rd harmonic of the seed frequency (3-9 THz) simply by adjusting the gap. Extensive modeling of the processes using 3-D time dependent code Genesis 1.3, which includes the space charge effect, confirmed a multi-MW power output and longitudinally modulated electron beam [7].

SEEDED 340 μM FEL MICROBUNCHING

As a first step in the THz FEL studies, we consider an experiment where the seed radiation wavelength will be fixed at 340 μm (~1 THz). The schematic of the experimental arrangement is shown in Fig. 1.

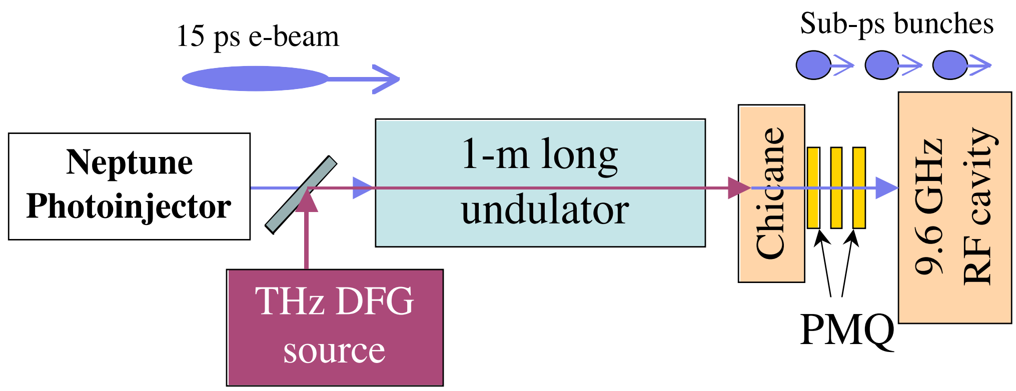

FIGURE 1. Schematic of the THz FEL microbunching experiment.

A 100 ps long THz seed pulse is produced by mixing the 10.3 and 10.6 μm CO_2 lines of the front end of the Neptune laser system via difference frequency generation (DFG) in a GaAs nonlinear crystal. Experimental results using 250 ps,, GW power CO_2 laser pulses indicate that an external conversion efficiency of 10^{-3} can be achieved for the THz DFG process [8]. Thus, by mixing beams containing an energy of 5 mJ per line, it is possible to generate a 1-5 μJ THz pulse using the 2.5 cm long GaAs crystal. This kW-power THz seed radiation is focused into the ~1-m long undulator. To confine the THz radiation beam and to preserve its linear polarization, the seed beam is guided in a metallic waveguide. The FEL interaction causes the electron beam to gain energy modulation. After leaving the undulator, the electrons are passing through the chicane where the energy modulation of the electron beam transfers to the current modulation. The microbunched electron beam will be injected into an existing RF deflecting cavity (X-band 9.4 GHz) which sweeps the electrons in time providing a resolution of <200 fs [9].

Results of simulations of FEL interactions obtained with the Genesis 1.3 code are shown in Fig. 2. For the Neptune undulator, the resonant interaction for the 340 μm radiation takes place when the beam energy is tuned to 7.25 MeV. A 30 A, 15 ps (FWHM) long electron beam with an energy spread of 0.2% is propagating collinear with a 1 KW seed pulse inside a metallic waveguide with an ID of 5 mm. The THz beam size for the TE_{01} mode is 1.5 mm that covers the whole wiggling motion amplitude (<650 μm) plus the electron beam transverse size. Note that the phase velocity increase of light inside the metal waveguide had to be taken into account in the simulations. The FEL amplification increases the seed power up to 300 kW (see Fig.2a). The bunching factor reaches 0.25-0.4. However, as seen in Fig. 2b, the microbunching is stronger at the head of the beam and weaker on the tail. This is attributed with the slippage effect occurring when the electron beam duration (15 ps) is shorter then 60 ps slippage generated in the undulator [2]. Sinusoidal energy modulation of the electron beam gained in the undulator is suitable for microbunching of the electron beam either by passing through the chicane or just 1-1.5 meters of the ballistic drift space before being sent to the RF deflector as shown in Fig.1.

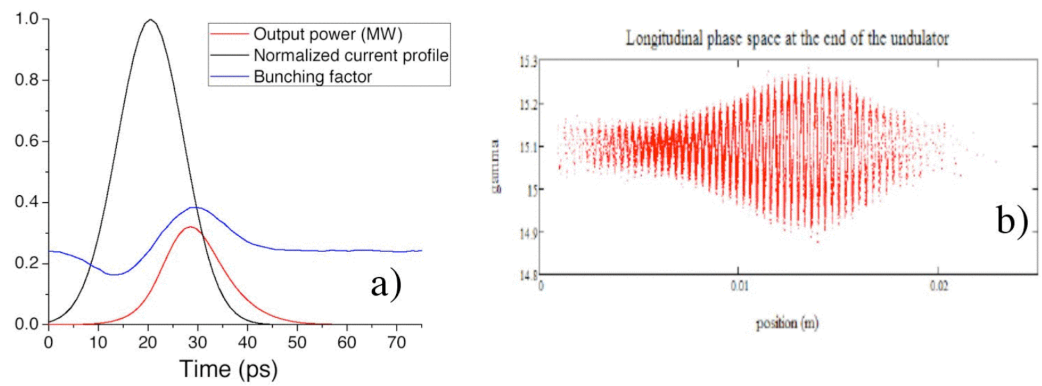

FIGURE 2. Time dependence of the THz output power, the beam current , and the bunching factor (a) and phase space distribution of the 7.5 MeV electron beam (b) at the exit of the 1-m long undulator at a seed power of 1 kW.

LWFA DRIVEN FEL SOURCE SEEDED AT 0.2-2 MICRONS

The pursuit of table-top short wavelength FELs is based on two rapidly developing technologies: high-gradient laser-plasma electron accelerators and single-pass UV/X-ray FELs driven by a high-brightness electron beam. The former has demonstrated quasi-monoenergetic electron bunches with an energy of up to ~1GeV. The latter has delivered unprecedented peak brilliance at 0.1 nm using the several-km long SLAC LINAC. The seeded FEL technique allows to combine the idea of a compact LWFA with a relatively short undulator because electrons interact with a seed radiation having intensity many orders of magnitude larger than the spontaneous noise.

A schematic of the seeded FEL experiment using a 20 TW Ti:sapphire laser driving the LWFA of electrons that are sent through the Neptune undulator is shown in Fig.3. A >100 MeV ultrashort electron beam is produced in a gas cell [4]. The beam is coupled in the undulator by a focusing permanent magnet. Small portion of the laser beam (0.1-

1 mJ) is sent to an optical parametric amplifier tunable in the range of 1.1-2.2 μm [5]. Thus by generating the second and the fourth harmonics of the IR radiation in nonlinear crystals, the entire 0.2-2 μm range can be covered with a 100 fs, 1-10 nJ seed. The seed pulse is sent collinearly with the electrons through the undulator which consists of two sections. This allows for measurements of the microbunched electron beam and analysis of the FEL dynamics at different stages of amplification.

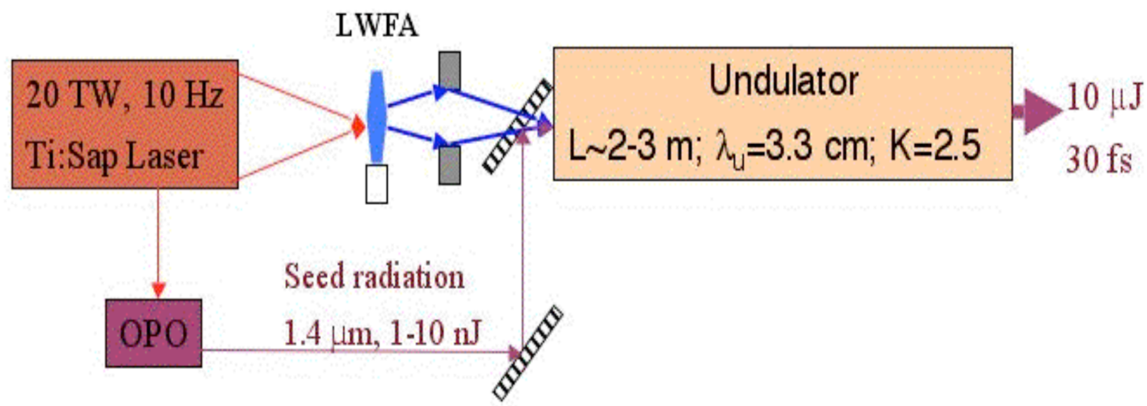

FIGURE 3. A simplified schematic of the LWFA driven FEL seeded at 1.4 μm. OPO is an optical parametric oscillator.

Table 2 shows the list of parameters used in the FEL simulations using Genesis 1.3. However, the basic scalings of the FEL can be evaluated by the Pierce parameter

$$\rho = \frac{1}{2\gamma}\left[\frac{I}{I_a}\left(\frac{KF\lambda_u}{2\pi\sigma_r}\right)^2\right]^{1/3} \tag{1}$$

where $\gamma = E_{beam}/mc^2$ is the electron beam energy, I is the peak current, I_a=17 kA is the Alfven current, σ_r is the beam size, $F=[J_0(\zeta)-J_1(\zeta)]$, $\zeta=K^2(4+2K^2)^{-1}$, and J_n are Bessel functions. For the parameters listed in table 2, the Pierce parameter is $\rho \approx 0.02$ and the gain length in a one dimensional approximation is $L_g=\lambda_u/4\pi\sqrt{3}\rho=0.08$ m. The Pierce parameter gives also an upper limit of the acceptable energy spread $\delta\gamma/\gamma$. Then in order to compensate for the relatively large energy spread of beams generated by the laser-plasma accelerator one needs to maximize the Pierce parameter. Thus, studying the seeded FEL physics in the 0.2-2.0 μm range, for which undulator parameters K and λ_u can be large and the electron beam energy $\gamma$is small, clearly more favourabel because of the increased ρ value. Operating at a large peak current helps to relax the electron beam quality requirements, but at a weaker scaling according to Eq. (1). Also the peak currents above the kA level for beams having an energy spread around 0.3-0.5% is very difficult to achieve in plasmas [4].

TABLE 2. Parameters of the LWFA driven FEL experiment.

E-beam				**Seed radiation**		**Undulator**	
Energy	112 MeV	Beam size	65 μm (rms)	Wavelength	1.4 μm	Period	3.3 cm
Current	1 kA	Length	25 fs FWHM	Seed power	~ 10 kW	K	2.506
Transverse emittance		1 mm-mrad		Length	~ 100 fs	Length	2+1 m

The results of modeling for the Neptune undulator seeded with a 10 kW, 1.4 μm pulse are presented in Fig. 4. In Fig. 4a it is seen that the output power after propagating through the 3-m long undulator reaches 250 MW and just starts to slow down. The FEL amplification is dominated by the slippage effect between the electron beam and the amplified radiation, since the 10 period long electron bunch propagates in the 60 (90) period long undulator. It is important that the 1.4 μm radiation profile in Fig.4b as a result of slippage is peaked on the front part of the electron beam, similar to that for the THz FEL case shown in Fig. 2a. This so called "weak superradiant" regime may result in a higher output power than that for a steady-state saturation [10]. By switching to a 200 nm seed, for which the slippage is much smaller, and corresponding increase of the beam energy, one can study this interesting FEL regime. It should be noted that the high-order harmonic FEL interactions would allow to use the 200 nm seed (0.2 μm x 7=1.4 μm) without change in the electron beam energy. Recently we have demonstrated efficient microbunching of the relativistic electron beam in a 7th order IFEL interaction [11]. Studying high-order harmonic FEL interactions for ultrashort electron bunches is another important physics aspect, since the technique allows for significant reduction in the beam energy without corresponding decrease in the undulator period and the magnetic field strength.

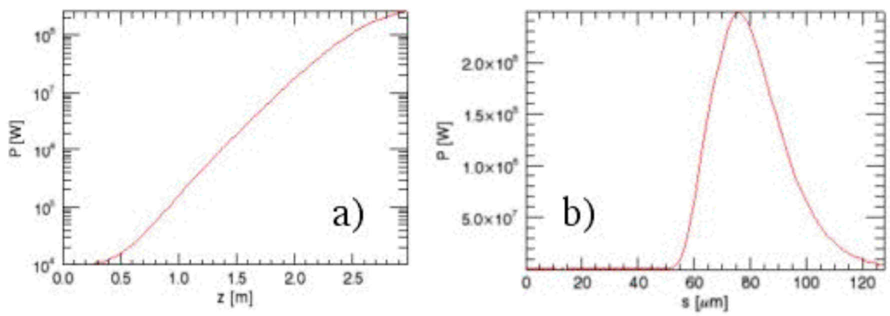

FIGURE 4. Calculated λ=1.4 μm power as a function of the undulator length z (a) and the radiation pulse profile at the exit of the undulator (b) for a seed power of 1kW and a peak current 1 kA.

SUMMARY

We have described an ongoing project on a single-pass seeded FEL amplifier-buncher at the UCLA Neptune Laboratory. The Neptune 2-m long and 1-m long undulators are fully characterized and ready for installation. For the THz experiments, when FEL is driven by the photoinjector, the seed power level between 10 W and 1kW is sufficient to generate MW power pulses in the range of 0.5-9 THz [7]. The initial study, however, is planned when only a short 1-m long undulator is seeded at 340 μm. Combination of time-resolved measurements of the longitudinal current distribution of the beam using the RF deflecting cavity and measurements of the THz undulator radiation will be used for the microbunching optimization. A seeded FEL scheme, when these undulators are driven by >100 MeV electron beam produced by the LWFA, is also presented. Seeding the undulators with 0.2-2.0 μm radiation allows to relax requirements for emittance, energy and energy spread of the ultrashort electron bunches generated in plasma. This makes it an ideal test bench for the FEL physics directly applicable to the future advanced UV/X-ray sources, for which the seed source is based on high-harmonic generation in gases.

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REFERENCES

1. G. Lambert et al , *Nature Phys*. **4**, 296 (2008).
2. C. Sung et al, *Phys. Rev. ST Accel.Beams* **9**, 120703 (2006).
3. W.D. Kimura et al, *Phys. Rev. Lett*., **92**, 054801 (2004); T.Plettner et al, *Phys. Rev. Lett*., **95**, 134801 (2005).
4. M. Fuchs et al, *Nature Phys,* **5**, 826 (2009).
5. P.E. Powers et al, *JOSA B*, **10**, 2162 (1993).
6. S.G. Anderson, M. Loh, P. Musumeci et al, “Commisioning and Measurements of the Neptune Photoinjector” in *Advanced Acceleration Concepts*, edited by P.L Colestock and S. Kelley., AIP Conference Proceedings 569, American Institute of Physics, Melville, NY, 2001, pp. 487-499.

7. S.Ya. Tochitsky, S. Reiche, C. Sung, et al, "Seeded FEL Amplifier-Buncher in the 0.5-9 THz Range for Advanced Accelerators" in *Advanced Acceleration Concepts*, 2008, edited by C.B. Schroeder, W. Leemans, and E. Esarey, AIP Conference Proceedings 1086, American Institute of Physics, Melville, NY, 2009, pp. 487-495.
8. S. Ya. Tochitsky et al, *J Appl. Phys*., **98**, 026101 (2005).
9. R.J. England et al, *Phys. Rev. Lett*., **100**, 214802 (2008).
10. R. Bonifacio et al, *Phys. Rev. A*, **40**, 4467 (1989).
11. S. Ya. Tochitsky et al, *Phys. Rev. ST Accel.Beams* **12**, 050703 (2009).