Seeded FEL Amplifier-Buncher in the 0.5-9 THz for Advanced Accelerators

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Abstract. Longitudinal modulation of a relativistic electron beam in the THz range is important for advanced laser- or beam-driven plasma accelerators operating in the $10^{16}$-$10^{18}$ cm\(^{-3}\) plasma density range. We describe a single-pass FEL amplifier-buncher which is under construction at the UCLA Neptune laboratory. Microbunching on the 0.5-3 THz frequency scale is achieved during the process of a resonant FEL interaction between an electron beam and a THz seed pulse. A narrow-band, low-power THz seed source based on the frequency mixing of CO\(_2\) laser lines in a GaAs nonlinear crystal is built and fully characterized. The THz radiation pulse generated by this source will be guided through a hollow waveguide inside the planar FEL undulator driven by a regular photocathode. By using a time-dependent FEL code GENESIS 1.3, we optimized the undulator parameters and analyzed the dynamics of the modulated electron beam. At present, the THz FEL microbuncher is being built and we update the status of the project.

INTRODUCTION

Seeded FEL/IFEL techniques can be used for modulation of a relativistic electron beam longitudinally on the seed radiation wavelength [1]. However, in the 1-10 THz range, which is of particular importance for the matched injection of prebunched electrons into a laser- or beam-driven plasma accelerating structure, a suitable seed radiation source, and therefore a microbuncher, is not available. At the Neptune Laboratory at UCLA we have launched an experimental program with the goal of developing a single-pass FEL amplifier-buncher seeded in the 0.5-3 THz range. The main objectives of the project are production of electron beams microbunched on the THz scale and generation of megawatt power pulses tunable in the range of 0.5-9 THz. It is important that current profile of the electron beam modulated on the THz wavelength scale can be measured directly, opening possibility to study an FEL beam-radiation interaction. From the radiation point of view, once installed the THz FEL may become the first US source capable of generating narrow-band tunable THz radiation pulses of MW power for testing different accelerating structures. Recently we have reported on a narrow-band THz seed source based on nonlinear frequency mixing of the CO\(_2\) laser lines in a GaAs crystal [2]. In this paper we present results of ongoing efforts towards this goal.
THZ FEL MICROBUNCHER AT NEPTUNE LABORATORY

The THz FEL microbuncher shown in Fig. 1 consists of four subsystems: an RF photoinjector, a THz seed source, an FEL undulator, and microbunching diagnostics. The S-band photoinjector at the Neptune Laboratory provides a 10-ps FWHM electron pulse with a peak current up to 100 A [3]. The relativistic (8-14 MeV) electron beam with an energy spread < 0.5% and a normalized emittance < 10 μm-mrad is propagated collinearly with a THz seed pulse and is focused down to 220 μm (σ_{r.m.s.}) at the entrance of the FEL undulator. The FEL undulator is a planar permanent magnet with a period of 3.3 cm designed in two sections: a ~2-m long (60 full periods) and a ~1-m long (30 periods) undulator separated by a chicane. Such an undulator configuration allows to study FEL interactions in 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. We consider three scenarios in the experiment using the FEL mechanism. 1) Frequency range 0.5-1.5 THz. A 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.

![FIGURE 1. Schematic of the THz FEL microbunching experiment.](image)

A 200 ns long THz seed pulse is generated by mixing two lines of a dual-beam CO₂ laser via difference frequency generation (DFG) in a GaAs nonlinear crystal. When various pairs of CO₂ laser lines are used, the step-tunable THz pulse with a step size of 30-40 GHz is generated in the range 0.5-3 THz [2]. This kW-power THz seed radiation is focused into the ~2-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 RF deflecting cavity (X-band 9.4 GHz) which sweeps the electrons in time providing a resolution of <100 fs [4].
It should be noted that our previous studies [5] considered kW seed power level in the entire range of 0.5-3 THz. However, as shown in Fig. 2 (triangles), in the experiment the seed power level for frequencies around 3THz (100 μm) falls to ~10 W due to a strong absorption in GaAs. The optical klystron scheme, when the first undulator is used as a modulator and the second undulator is a radiator, allows to compensate for the lack of a seed power. In the next section we analyze via simulations all three THz FEL scenarios.

![THz peak power in the THz range. Solid line represents a calculated DFG power without taking into account absorption in GaAs.](image)

**FIGURE 2.** THz DFG peak power in the THz range. Solid line represents a calculated DFG power without taking into account absorption in GaAs.

### 3D SIMULATIONS OF THE THZ FEL INTERACTION

A three-dimensional, time-dependent simulation code, Genesis 1.3 is used for modeling the FEL amplification and microbunching process in the waveguide. Genesis 1.3 solves a set of self-consistent differential equations based on Maxwell’s and Hamilton’s equations that describe the physics of an FEL, including the space charge effect [6]. Table 1 shows the list of parameters used in the FEL simulations. Note that with our undulator design, the tunability of the seeded FEL microbunching can be achieved by injecting a seed pulse with different wavelengths and an electron beam with an energy γ matching the FEL resonance condition.

| Table 1: Parameters of the Neptune THz FEL microbunching experiment |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| **E-beam** | **THz radiation** | **Undulator** |
| Energy | 8-14 MeV | Wavelength | 100-500 μm | Period | 3.3 cm |
| Current | 20-60 A | Seed power | ~ 1 kW | K | 2.506 |
| Transverse emittance | 5-15 mm-mrad | Length | ~ 200 ns | Gap | 8-20 mm |

In Fig. 3 we show the phase space distribution of the whole 10-ps long (FWHM) electron beam after interacting with a 1 kW seed pulse in a 2-m long undulator. At the exit of the undulator without the chicane the 12 MeV beam with a peak current of 60 A is nicely bunched with a period of 124 μm. Note that by switching to a higher (lower) current of the electron beam one can increase (decrease) the FEL gain and optimize the microbunching process by the beam current control. As seen in Fig. 3, the tail of the beam is left almost unmodulated. This is attributed to a slippage effect [5].
In an FEL the newly emitted radiation always overtakes the electrons that generate it and electrons constantly “see” the radiation amplified by other electrons behind them. For a short electron pulse produced by a photoinjector, the number of periods of the wave covering the electron beam is smaller than the number of undulator periods. Therefore, for the electrons from the head and the center of the pulse, the amount of THz photons is larger and the energy modulation is stronger.

![Graph showing phase space distribution of the 12 MeV electron beam at the exit of the undulator at a seed power of 1kW, peak current 60 A, and \( \lambda = 124 \mu m \).](image1)

**FIGURE 3.** Phase space distribution of the 12 MeV electron beam at the exit of the undulator at a seed power of 1kW, peak current 60 A, and \( \lambda = 124 \mu m \).

For a smaller seed power in the range 10-100 W and the same 12 MeV beam one must use the chicane in order to achieve optimal microbunching. This is demonstrated in Fig. 4, where the THz peak power after the second undulator-radiator is plotted as a function of the \( R_{56} \) element of the chicane for different seed powers. By using the chicane one can obtain a current modulated beam at a distance of 0.5-1.0 m from the first undulator. At this point, either an RF deflector or simply a coherent transition radiation screen, can be installed to diagnose microbunching. In this particular case the second undulator located at \( \sim 0.6 \) m is used as a diagnostic for measuring the degree of current modulation. The emitted power peaks around \( R_{56} = 2 \) cm, which corresponds to a chicane magnetic field strength of \( \sim 0.2 \) T. It should be noted that seeding a 10 W pulse in the undulator-modulator results in a 4 MW peak power for the output THz pulse.

![Graph showing THz power at 124 \( \mu m \) produced by the optical klystron as a function of the \( R_{56} \) element of the chicane.](image2)

**FIGURE 4.** THz power at 124 \( \mu m \) produced by the optical klystron as a function of the \( R_{56} \) element of the chicane.
Fig. 5 shows the data for the case when the gap in the 1-m long undulator-radiator is increased to match the 3rd harmonic resonance of the seed frequency (HGHG scheme). For a 100 W seed power sent into the undulator-modulator, the maximum output power from the undulator-radiator is observed at $R_{5g}=1\,\text{cm}$. Shift to smaller values of the optimal chicane magnetic field in comparison with that in Fig.4 can be attributed to an optimal radiation production when a slightly underbunched beam is injected in the second undulator. The quality of electron beam microbunching after the second undulator may deteriorate in a non-seeded FEL interaction and needs to be studied. However, HGHG results in a high-power 0.4 MW pulse at 41 $\mu\text{m}$ where other sources are scarce.

![Figure 5](image)

**FIGURE 5.** THz power at 41 $\mu\text{m}$ produced by the 12 MeV electron beam in an optical klystron as a function of the $R_{5g}$ element of the chicane.

**STATUS OF THE EXPERIMENT**

Recently, a cooperation has been launched between STI Optronics, Inc. and UCLA in order to design and build the waveguide THz FEL amplifier-buncher. The undulator parameters used for the THz FEL design are presented in Table 1. This undulator strength can be achieved with an existing technology for a permanent magnet planar undulator with a variable gap of 8-20 mm. In Fig.6 we present a drawing of the 2-m

![Figure 6](image)

**FIGURE 6.** THz FEL microbuncher with the chicane, vacuum boxes and the waveguide placed on the optical table.
long THz FEL buncher with an optical table, chicane and vacuum boxes to couple (decouple) the THz radiation pulse in the waveguide. The key issue in designing this undulator is pole shaping in order to achieve two-plane homogeneous focusing and to maintain the optimum electron beam profile inside the waveguide FEL. We chose the poles with a 6th order parabolic profile which according to an FEA modeling is adequate for the THz microbuncher. The chicane is a permanent three-pole magnet with an adjustable gap and the magnetic field varied within 0-0.4 T. The 1-m long undulator-radiator is a table-top device not shown in Fig.6. At present the described magnets are being manufactured by STI Optronics, Inc.

SUMMARY

Using 3D simulations we have shown that the optical klystron configuration: 2-m long undulator – chicane –1-m long undulator, allows to microbunch the electron beam on the 0.5-3 THz scale and to produce MW power pulses in the range of 0.5-9 THz. The seed power level between 10 W and 1kW demonstrated in the experiment [2] is sufficient for THz FEL microbunching. 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 microbunching optimization. The HGHG scheme when the second undulator is tuned to the 3rd harmonic of the seed resonant frequency provides an access to the 3-9 THz spectral window. Experimental study on feasibility of using HGHG for microbunching is required. All the magnets are currently being manufactured and the THz FEL amplifier-buncher will be installed in 2009.

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REFERENCES