FEASIBILITY STUDY OF A BEAT-WAVE SEEDED THz FEL AT THE NEPTUNE LABORATORY

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Abstract

Free-Electron Laser in the THz range can be used to generate high output power radiation or to modulate the electron beam longitudinally on the radiation wavelength scale. Microbunching on the scale of 1-5 THz is of particular importance for potential phase-locking of a modulated electron beam to a laser-driven plasma accelerating structure. However the lack of a seeding source for the FEL at this spectral range limits operation to a SASE FEL only, which denies a subpicosecond synchronization of the current modulation or radiation with an external laser source. One possibility to overcome this problem is to seed the FEL with two external laser beams, which difference (beat-wave) frequency is matched to the resonant FEL frequency in the THz range. In this presentation we study feasibility of an experiment on laser beat-wave injection in the THz FEL considered at the UCLA Neptune Laboratory, where both a high brightness photoinjector and a two-wavelength, TW-class CO_2 laser system exist. By incorporating the energy modulation of the electron beam by the ponderomotive force of the beat-wave in a modified version of the time-dependent FEL code Genesis 1.3, the performance of a FEL at Neptune is simulated and analyzed.

INTRODUCTION

Free-Electron Lasers (FEL) [1] have been demonstrated successfully down to a wavelength of below 100 nm [2]. These radiation sources allow for a tunable wavelength and do not rely on a seeding signal, which are difficult to obtain in the X-ray but also THz regime. Instead the FEL process can be initiated by either an initial current or energy modulation. The former is the driving mechanism of Self-Amplified Spontaneous Radiation (SASE) FELs [3, 4], while the latter has not been considered for experiments so far.

In this paper we consider the latter method to generate a seed for a THz FEL. The energy modulation is generated by the beat-wave of two laser pulses, whose individual frequencies are not resonant with the FEL, but the difference frequency is. Although the mechanism works for two co-propagating plane waves its efficiency is strongly reduced [5]. Instead we consider the laser beat-wave (LBW) of two strongly focused Gaussian modes [6]. The interaction is confined within a few Rayleigh lengths around the focus position. The energy modulation and thus the emitted THz radiation is phase-locked with the laser signal, in contrast to SASE FELs, which start from an arbitrary phase and which require significant more undulator length than the system, discussed in this paper. Note that this phase-locking is critical for injection of a prebunched electron beam into a plasma beat-wave accelerator [7]

MODELING OF THE BEAT-WAVE INTERACTION

To study the interaction of an electron beam with a LBW and the resonant emission within a periodic magnetic field of an undulator, an analytical model for the interaction is derived and incorporated into the Free-electron laser code Genesis 1.3. Although for this paper the process of energy modulation and the emission of radiation is well separated a more general problem can be described with our model, where the overlap between electron beam and LBW can happen within the undulator.

The normalized, transverse electric field component for a fundamental Gaussian is given by $a_x(z) = a(z)\cos\phi$ with the amplitude

$$a(z) = \frac{eE_0}{kmc^2}\frac{1}{\sqrt{1+(z/z_0)^2}}\exp\left(-\frac{r^2}{w^2(z)}\right) \qquad (1)$$

and phase

$$\phi = kz - \omega t + \frac{r^2}{w^2(z)}\frac{z}{z_0} - \tan^{-1}\left(\frac{z}{z_0}\right), \qquad (2)$$

where z is the longitudinal position with respect to the waist position, z_0 is the Rayleigh length, k is the wavenumber, ω is the frequency, E_0 is the electric field amplitude and $w(z) = w_0\sqrt{1+(z/z_0)^2}$ is the waist size of the Gaussian mode. The resulting oscillation in the electron orbit is then in good approximation $\Delta x = (2\gamma/k)a(z)\cos\phi$. The transverse oscillation pushes even electrons initially on-axis to an offset where the longitudinal electric field is not zero. For the fundamental Gaussian mode the normalized, longitudinal electric field is

$$a_z(z) = 2\frac{x}{z_0}\frac{a(z)}{1-(z/z_0)^2}\left(\sin\phi - \frac{z}{z_0}\cos\phi\right). \qquad (3)$$

It can be easily shown by symmetry reasons that a single mode cannot yield a net energy transfer from the radiation field to the electron. However the situation is changed if two Gaussian modes, which differ only in frequency, are superimposed [6, 8]. The effective amplitude $a(z)$ is then scaled with the low frequency beatwave $a(z) \to a(z)\cos\Phi$ with

$$\Phi = \frac{\Delta k}{2}z - \frac{\Delta\omega}{2}t = \Phi_0 - \frac{\Delta k}{4\gamma^2}z, \qquad (4)$$

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where we evaluated in the last step the radiation phase as seen by the electron ($z = c\beta_z t$). The change in the electron energy is then

$$\frac{d\gamma}{dz} = \frac{z}{z_0^2}\frac{\gamma a(z)^2}{1+(z/z_0)^2}\cos^2\Phi. \qquad (5)$$

We dropped the fast oscillating terms of the high frequency beat wave and the negligible effect from the magnetic field of the Gaussian modes. Because the LBW phase Φ is not symmetric in z for all electrons some electrons are gaining energy while other are loosing it. As a result an energy modulation is imprinted on the electron beam with the periodicity of $\lambda_{mod} = \lambda_1\lambda_2/(\lambda_1 - \lambda_2)$, where $\lambda_{1,2}$ are the wavelengths of the Gaussian modes.

To model the interaction of an electron beam with a LBW and the succeeding emission in an undulator, tuned to the periodicity of the energy modulation, the 3D FEL code Genesis 1.3 has been extended to include the analytical solution for the energy modulation (Eq. 5). The impact of the fast oscillating $\lambda_{1,2}$ waves as well as the energy modulation, caused by the magnetic field of the Gaussian modes, has been ignored. The interaction phase Φ is integrated piece-wise with an integration step length much shorter than the Rayleigh length of the modes.

THE NEPTUNE INJECTOR

Currently the Neptune Laboratory [9] hosts a TW-class, two-wavelength CO_2 laser system and a high-brightness photoinjector necessary for the proposed LBW seeded THz FEL experiment. Although direct injection of LBW into the THz undulator will uncover a new mechanism for seeding FELs, it requires a relatively long undulator. That is why as the first phase of the experiment we consider a configuration where LBW-driven acceleration (energy modulation) and FEL interaction are separated in space. In the case of successful implementation, during the second phase we plan to use a 2-m long undulator for seeding the FEL with an energy modulated beam and producing THz pulses of MW power level.

A conceptual design of the LBW seeded FEL experiment is shown in Fig. 1. Here the two-wavelength laser beam with a peak power of around 1 TW (200 J, 200 ps) is focused into the vacuum chamber. For our experiment we consider the LBW between the 10.6 and 10.3 μm lines ($\lambda_{mod} \approx 340$ μm) as well as 10.6 and 9.6 μm lines ($\lambda_{mod} \approx 100$ μm). At the point of interaction the laser beam size w_0 is 300 μm with a Rayleigh range of 1.5 cm. A 10 MeV, 12 ps (FWHM) electron beam is focused in the same plane to a 200 μm (RMS) spot size. We anticipate the bunches with a charge well in excess of 0.5 nC will be produced providing a peak current of 60 A.

Interaction of the electron beam and the LBW results in ponderomotive acceleration and energy modulation on the THz scale. This stage is followed by a ballistic drift of the electrons over approximately a 1-m long distance, where the gained energy modulation transfers to the beam current modulation. The CO_2 laser beam is transported out the vacuum and could be recycled. Installed here a quadrupole triplet matches the beam envelope to the natural focusing of the undulator. In the undulator owing to the current modulation a coherent start-up of THz generation takes place. A short, 33-cm long undulator magnet with a period of 3.3 cm and a K value between 1.7-3.3 is planed to use. The undulator design provides no focusing in the wiggle plain. The THz undulator radiation as well as the coherent transition radiation will be transported in a waveguide to a Golay cell detector. Analysis of THz radiation is considered the main diagnostics for both ponderomotive and FEL microbunching.

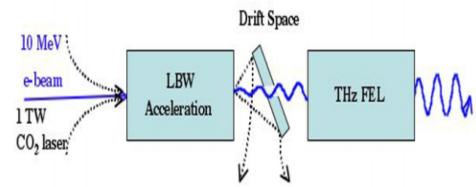

Figure 1: Conceptional design for the Neptune experiment.

THE EXPECTED PERFORMANCE

The goal for the beat-wave interaction is to maximize the output radiation power at the end of the undulator. Due to some space constraints and the availability of an undulator the length of the undulator is fixed and the gap is tuned to yield a resonance wavelength identical to the periodicity in the induced energy modulation. The electron beam energy is set to γ=20 as the reference energy. For our modeling we assume the rather pessimistic values of 10 keV for the intrinsic energy spread and 16 mm·mrad for the emittance.

Two LBA wavelength of 350 μm and 100 μm are considered. The case of the longer wavelength has the disadvantage that first, the required length to achieve optimum bunching is about 3.5 times longer for a given energy modulation than for the short wavelength case. Second, more electrons per wavelength are bunched, resulting in a stronger space charge field. The performance at 350 μm is much inferior than for 102 μm and is not further discussed.

The optimization of the THz radiation depends solely on the interaction between the laser field and electron beam, because all other parameters are either fixed by the constraints of the Neptune facility or shown no impact, e.g. a waveguide within the undulator does not improve the radiation power because the emitted radiation is spontaneous. The length of the undulator is too short to start the FEL amplification which then could benefit from the reduced diffraction by a waveguide.

We study the impact on various parameters on the output power, which is the waist position, radiation power and waist size. The reference case has a perfect overlap of

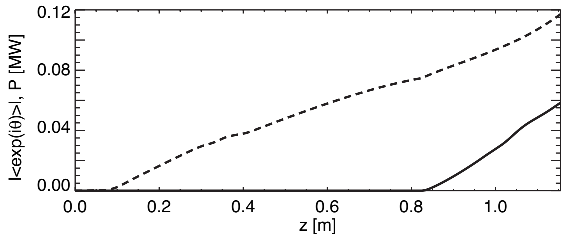

Figure 2: Growth of the radiation power and current modulation (solid and dashed line, respectively) at 102 μm along the Neptune beam line. The waist position of the LBW is positioned at $z = 9$ cm.

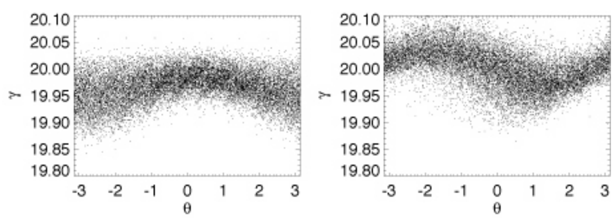

Figure 3: Longitudinal phase space distribution ($\theta = (2\pi c/\lambda)t, \gamma$)at the waist position of the LBW and at the exit of the undulator (left and right plot, respectively) for λ=102 μm.

the waist position and electron beam waist with a radiation power of 500 GW per laser line. The laser intensity in the focus is reaching $3.5 \cdot 10^{14}$ W/cm^2. The growth in the current modulation and radiation power is shown in Fig. 2. After the interaction region at z = 9 cm the current modulation grows almost linearly except for the impact of the focusing quadrupole triplet at z=40 cm and the growing space charge field before the undulator (z=80 cm), which removes the energy modulation. Within the undulator the dispersion is enhanced by the magnetic field of the undulator. The spread in the relative velocity of the electrons is enhanced, which allows to further overcome the counteracting effect of space charge. The output power of the radiation is 60 kW. Longitudinal phase space plots at the focus of the LBS interaction and at the end of the undulator are shown in Fig. 3.

The tolerance on the longitudinal overlap of the waist in the radiation field and electron beam is relaxed and allows for an error of more than one Rayleigh length. The output power scales quadratically with the power of the LBW (left plot of Fig. 4). The energy modulation (Eq. 5) and thus the resulting current emission scales linearly with the laser power, while the coherent emission is quadratic in the current modulation. The dependence on the waist size is more complex (right plot of Fig. 4). The best result is achieved if the laser beam is focused below the size of the electron beam. In this case the energy modulation is strong for on-axis electrons but has a wide spread towards electrons with

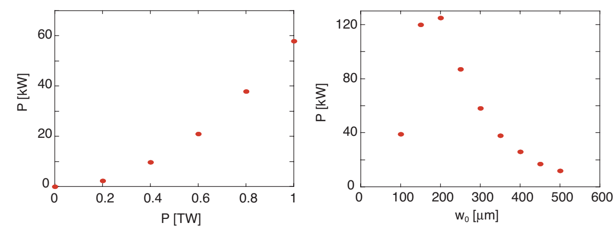

Figure 4: Dependence of the undulator radiation output power on the total power and waist size of the laser beatwave (left and right plot, respectively).

larger betatron amplitude. On-axis electrons will achieve maximum bunching at the end of the undulator thus emitting fully coherent with maximum power. However for a more uniform energy modulation of all electrons the waist size should be larger than the electron beam size. This would be the favorable mode of operation if it would be possible to extend the undulator beyond 33 cm, where the FEL process could trap the energy and current modulation and preserve it along the undulator.

Operating at γ=24 increases the output power by 20% due to the stronger rigidity of the electron beam, the stronger emission of undulator radiation for a larger undulator parameter and the increased dispersion within the undulator.

CONCLUSION

The feasibility study shows that parameters of Neptune photoinjector and CO_2 laser system are sufficient to demonstrate LBW seeded FEL microbunching on THz scale. The experiment will examine for the first time a concept of ponderomotive acceleration and microbunching in vacuum. Seeding the undulator of sufficient length with an electron beam modulated at LBW frequency opens the possibility to generate a high-power THz pulses in a single-pass high-gain FEL where the seed source is not available.

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