Study of a THz IFEL prebuncher
for laser-plasma accelerators

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Abstract. For monoenergetic acceleration of electrons, the injected particles need to be bunched with the same periodicity as the accelerating structure. In a laser-driven plasma beatwave accelerator, the accelerating structure (plasma wave) is phase-locked to the CO_2 beat-wave used to drive it. Using the same beat-wave to generate high power FIR radiation via difference frequency mixing in GaAs ensures that the radiation has the same phase relationship as the plasma wave before it saturates and detunes from the pump. Therefore, this radiation can be used to prebunch an existing electron beam based on an Inverse Free Electron Laser (IFEL) concept. Here we report the progress on the proposed THz microbunching experiment in the Neptune laboratory. A 50 cm long prebuncher is optimized using simulation codes for minimum FIR power required. The injected 5ps long electron beam is expected to form a series of 45 μm long microbunches containing over 40% of the injected current after 1.6 m drift space following the undulator. Preliminary experimental results on THz generation are also presented.

1. INTRODUCTION

Due to the limitation of the energy gain gradient and cost efficiency of conventional RF-based accelerators, advanced accelerating concepts, such as laser or electron driven plasma waves based structures, have been proposed as potential solutions for the next generation accelerators and studied worldwide [1]. In recent years, proof-of principle experiments have shown gradients much higher than conventional accelerators [2] in a short distance. However, low quality of the electron beam produced by plasma-based accelerators, for example, the energy spread is continuous, practically limits acceleration to one stage. Therefore, it is of great importance to demonstrate matched injection of an electron beam in a plasma LINAC to produce a high-quality beam potentially suitable for staging.

In the plasma LINAC, in order to obtain monoenergetic acceleration of electrons, the injected particles need to be bunched on a scale shorter than the wavelength of the accelerating structure and with the same periodicity. For a plasma wave resonantly driven at plasma densities 10^{16}-10^{17} cm^{-3}, the plasma wavelength λ_p is equal to 340-

100 μm, respectively. In order to inject electrons into a narrow phase interval of the plasma wave, an electron beam needs to be prebunched into a series of ~50-15 μm long microbunches that separated by the plasma wavelength. An inverse Free Electron Laser (IFEL) technique – an efficient method to produce a train of microbunches at a wavelength as short as 10 μm for a stiff relativistic electron beam [3] – can be utilized to modulate an electron beam on the plasma wavelength scale if a suitable high-power FIR source is developed. The comb of CO_2 laser lines is an ideal source for generating step tunable radiation in the FIR range of 100-1000 μm through difference frequency generation (DFG) in a nonlinear crystal. Thus there is a strong motivation both to develop a DFG-based source of FIR radiation and to demonstrate microbunching of electrons for laser-plasma accelerators in the 10^{16}-10^{17} cm^{-3} density range.

   For the CO_2 laser driven Plasma Beatwave Accelerator (PBWA) experiment at the Neptune laboratory where λ_p =340 μm (~1THz), it was proposed to use a THz IFEL prebuncher for producing short, 50 μm electron bunches phase-locked with the accelerating structure [4]. Phase-locking between the electrons and PBWA becomes possible since the same laser beatwave is used to excite the relativistic plasma wave and to generate THz radiation via DFG in GaAs to drive the IFEL prebuncher.

   In this paper, we report on our progress towards the proposed THz microbunching of electrons. First, we present results of detailed 3-D modeling of IFEL microbunching including beam propagation in a several meter long drifting space following the prebuncher. The optimization of the prebuncher design is carried out for minimizing the required level of THz power. Second, we report preliminary experimental results on generating THz radiation in GaAs. It is the first experimental measurements of THz signals produced by DFG using 300 ps, high-power CO_2 laser pulses.

2. IFEL MICROBUNCHING AT NEPTUNE LABORATORY

   In the PBWA experiment at the Neptune Laboratory at UCLA, two lines of a CO_2 laser (10.6 and 10.3 μm) are used to excite a relativistic plasma beat wave (λ_p =340 μm) with an acceleration gradient ~ 1-3 GeV/m [5].
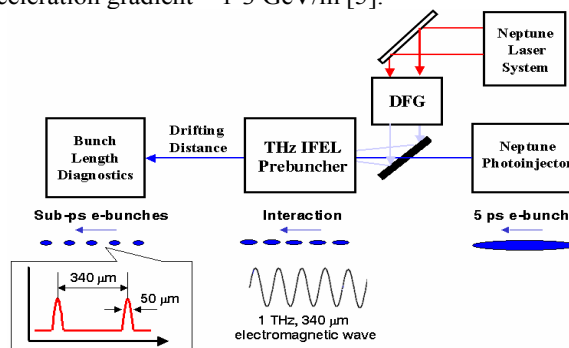

FIGURE 1. Schematic of THz microbunching experiments at Neptune Lab, UCLA

As shown in Fig. 1, a high-power, two-wavelength CO_2 laser beam is sent into a nonlinear crystal (GaAs) for DFG. This newborn radiation will be focused and sent collinearly into a planar IFEL prebuncher with a 10 MeV electron beam coupled through a hole in a mirror. The electron beam coming from a photoinjector will interact with the THz radiation via IFEL mechanism while going through the undulator and get bunched while drifting in the free space. Since the 340 μm wave originates from the same two wavelengths that drive the plasma beat waves, those microbunches potentially can be used for phase-locked injection in the PBWA. After drifting in a vacuum over approximately 1.5-2 m the bunched beam will be analyzed using different bunch length diagnostics. Several techniques such as OTR/Cherenkov measurements, electro-optical sampling and a RF cavity reflector [6] are considered. It is important that on the THz scale direct measurement of longitudinal dynamics of electron bunches is still possible.

3. PHYSICAL PICTURE OF IFEL BUNCHING AND SIMULATION RESULTS

An IFEL undulator is an array of permanent magnets with their polarization alternatively aligned. When electrons wiggle along the axis of such an undulator, the EM wave can modulate the energy of electrons. Under certain conditions,. Such an energy-modulated beam can be compressed after drifting an optimal distance. If an electron experiences a full cycle of changing of electric field while wiggling one period in the undulator, it is called the resonant condition:

$$\lambda = \frac{\lambda_w}{2 \cdot \gamma^2} \cdot \left(1 + \frac{K^2}{2}\right),$$

and the undulator dimensionless parameter $K = eB_w/mc^2k_w$, where λ is the radiation wavelength, γ the electron energy, λ_w the undulator wavelength, k_w the undulator wave number and B_w the undulator magnetic field. Under this condition, particles that see the accelerating phase in each wavelength gain energy in the whole wiggling process and those seeing decelerating phases keep losing it. Faster electrons then catch up with slower ones while wiggling in the buncher and drifting in the free space. As a result, microbunches form with the same periodicity as the radiation wavelength. After the optimal bunching position, fast electrons overtake slower ones and debunching occurs.

In a planar IFEL undulator, equations describing the motion of electrons are:

$$\frac{\partial \gamma}{\partial z} = \frac{K}{\gamma} \cdot \frac{k K_L}{\sqrt{1 + \frac{(z - z_w)^2}{Z_r^2}}} \cdot \frac{JJ(K)}{2} \sin(\psi)$$

$$\frac{\partial \psi}{\partial z} = k_w + k - \frac{k}{\left(1 - \frac{1 + \frac{K^2}{2} + \frac{K_L}{2} + K K_L \cdot JJ(K) \cdot \cos(\psi)}{\gamma^2}\right)^{1/2}} - \frac{1}{Z_r\left(1 + \frac{(z - z_w)^2}{Z_r^2}\right)}$$

where K_L is the radiation dimensionless parameter (eE_o/mc^2k), Ψ is the phase of coupling between the wiggling motion and the EM wave ($\Psi = (k+k_w)z-wt$), and JJ is the Bessel factor due to the planar geometry. Those equations show that for a given electron energy γ and same radiation power, the larger the K of the undulator, the stronger the energy modulation is imposed on the electrons.

There are two codes that we use to optimize the undulator design and to model the IFEL bunching effect. The 1-D code solves the equations of motions and calculates the phase and energy of each electron at any longitudinal position. The other is a 3-D code called TREDI that calculates the Lorenz force acting on each electron and calculates its position and energy along time. We first roughly determined parameters of the undulator using the 1-D code and then finalized calculations with the TREDI code. Note that the results obtained by both codes are very similar.

The goal of simulations at this stage is to find the minimum FIR power required to bunch an electron beam with (a) bunch length (FWHM) of less than 50μm ($\lambda_p/7$) with a number of trapped particles larger than 40%, and (b) optimal microbunching obtained at a reasonable drifting distance of approximately 1.5-2m.
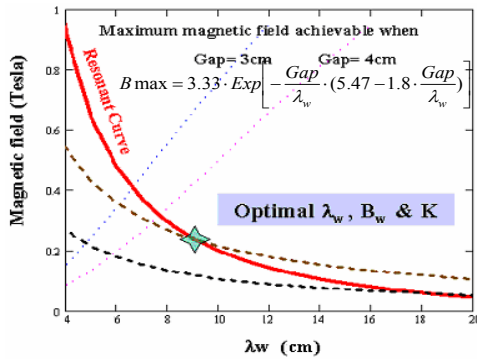

$$B\max = 3.33 \cdot Exp\left[-\frac{Gap}{\lambda_w} \cdot (5.47 - 1.8 \cdot \frac{Gap}{\lambda_w})\right]$$

FIGURE 2: Chart for the undulator parameters

Fig. 2 shows the optimization of the undulator parameters. λ_w and B_w are chosen along the solid cure to satisfy the resonant condition and to make K as large as possible to maximize the bunching effect. However, the Halbach formula limits the choices because of the physical restriction in building magnets with small periods. The gap between the magnets is setup to accommodate the FIR beam inside the undulator. For simplicity, we chose an undulator with 4 cm gap, λ_w=9cm, and B_w=0.24 T (K=2) for following simulations in a diffraction dominated case.

With those initial undulator parameters, we run 1-D simulations varying the FIR power and the undulator length. The results are shown in Fig. 3. To satisfy conditions (a) and (b), undulator length L_u can be chosen longer than 50 cm, and the minimum FIR power requirement is around 10MW when the Rayleigh range is equal to the undulator length. In those cases, the amount of trapped particles is larger than 40%. This results were fully confirmed in 3-D simulations.
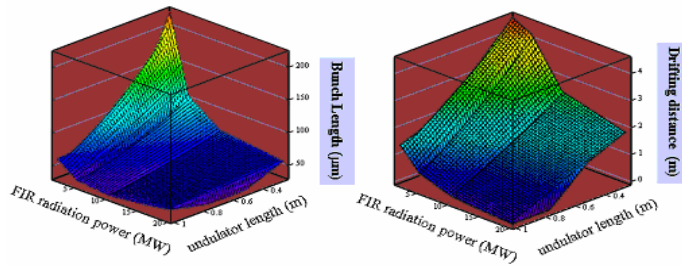
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FIGURE 3: 1-D simulation results on bunching with various FIR power and undulator lengths. (Using an undulator with 4 cm gap, λ_w=9cm, and B_w=0.24 T (K=2), and γ=20)

In Fig. 4, shown is the phase space distribution of electrons in one bucket and its histogram obtained by using the TREDI code. From the histogram, we deduce that the bunch length of 45 μm for 40% trapped particles is obtained at the optimal drifting distance of 1.6 m. Note that the bunch length less than 50μm can be preserved for over 1 m. This large value of the acceptance length is important for future experiments. The undulator, FIR parameters and the optimal bunching results are summarized in Table 1.
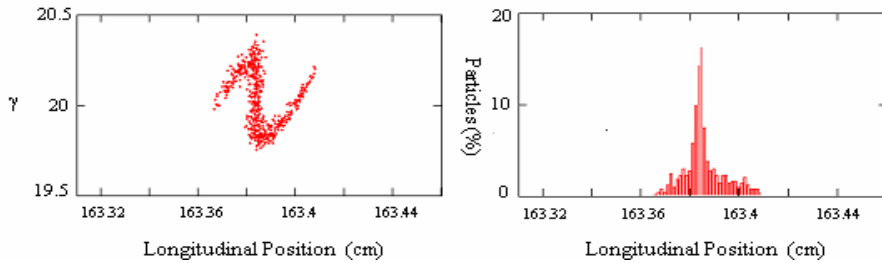

FIGURE 4: Phase space distribution and histogram of electrons in one period of the EM wave.

TABLE 1: Important input and output parameters in the optimal bunching case of TREDI simulations

THz radiation power	10 MW (I_{peak}=5.9 MW/cm^2)
Injection e⁻ energy	10 MeV (0.25% energy spread)
Undulator length	0.5 m
Undulator wavelength	0.09 m
Permanent magnet	0.237 T
K factor	2
Bunch length	**45 μm**
Trapped particles	**40%**
Bunching distance	**1.6 m**

Thus the values we obtained in simulations are feasible for future experiments: the easy-to-build undulator parameters produced the desired bunch length and 0amount of trapped particles after a reasonable bunching distance. Further decrease in the required FIR power to ~1MW and less may be possible if THz beam will be guided in a hollow waveguide with subsequent decrease of the undulator gap to less than 1 cm.

It is interesting that, as shown in [4], the same undulator design can be used to bunch electrons on higher harmonics of the resonant frequency. Therefore, in our case, we can study microbunching of electrons for a plasma density ~10^{17} cm^{-3} (λ_p=114 μm).

4. PRELIMINARY EXPERIMENTAL RESULTS
ON THZ RADIATION GENERATION

We are presently carrying out experiments on generating THz radiation via DFG at the Neptune laboratory using high-power, 300 ps laser pulses. The 10.6μm and 10.3 μm CO_2 laser beams were sent on a GaAs crystal according to a noncollinear phase-matching configuration [4,7]. The optical scheme of the experiment is shown in Fig. 5.
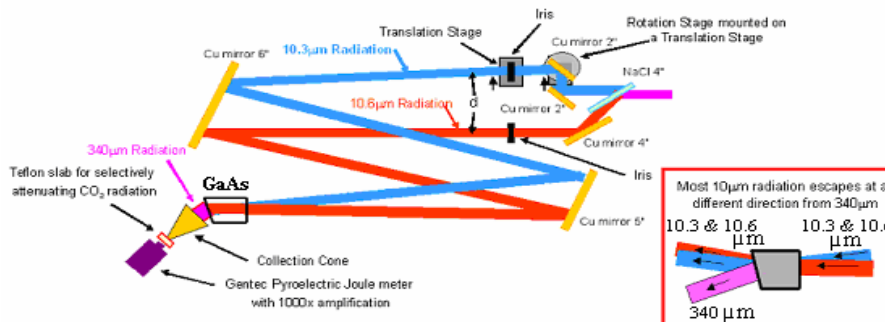

Figure 5. Optical scheme for the THz generation in GaAs

Here a vertically polarized, two-wavelength CO_2 laser beam is split into two optical arms. Because of the orientation of the crystal, only one wavelength in each arm is participating in difference frequency mixing. The 10.6 μm arm is aligned at a normal to the front surface of the crystal. The 10.3 arm is adjusted to scan the internal phase matching angle. A 2x4x2.5cm GaAs crystal is cut in such a way that the newborn radiation is separated from the pump lasers due to refraction at the crystal to air interface (see the insert in Fig. 5). The THz radiation is collected by a cone and sent through a Teflon slab (10 μm radiation attenuator) into a Gentec detector equipped with a 1000X amplifier. For a very long base of both arms, we achieve an angle resolution of less than 0.01^o while scanning the phase matching angle. The preliminary data on THz generation is shown in Fig. 6.
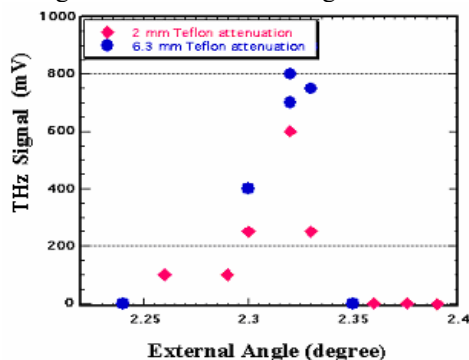

FIGURE 6. Phase matching angle dependence for THz generation

In Fig. 6, we can see the angular dependence of measured THz signals. The phase matching angle corresponded to the peak signal and the angle width are consistent with the theoretical predications for a 2.5 cm long crystal. Similar signals obtained with different attenuation points that there is no residual 10 μm radiation. Assuming flat spectral response of a Gentec energy meter from 1 to 28 THz, at least 40 kW of FIR was generated in GaAs. For the best shots up to ~1.25 J (300mJ at 10.6 μm and 200mJ at 10.3 μm participated in DFG) was sent on the crystal.

It is known that nonlinear frequency conversion for a pulsed beam is limited by the surface damage threshold of the material. In a series of damage threshold measurements, we observed a single shot damage of GaAs at $\sim 0.5/cm^2$ (~ 1.6 GW/cm^2). However, in the experiment for a 2 cm beam, existence of the hot spots seriously limited the incident fluence especially for multishot exposure. We believe that a large aperture (~5") crystal and a corresponding CO_2 laser beam of high-optical homogeneity are needed to achieve THz power in multi-megawatt range without damaging crystal. This is the subject of future work.

5. CONCLUSIONS

In this paper, feasibility of prebunching an electron beam for laser-plasma accelerators with various densities has been studied. An undulator design is optimized for the strongest bunching. According to simulations, a bunch length less than 50 μm can be achieved with a ~ 6 MW/cm^2 level intensity of THz radiation. Preliminary experimental results confirm that DFG can be used to provide such FIR radiation, however, further improvements and studies are needed, such as improving the pump beam profiles, optimizing the phase-matching scheme, guiding of THz radiation, or adding a chicane to shorten the drifting distance.

6. ACKNOWLEDGMENTS

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