Bunched Beam Injection in a Plasma Accelerator

S. Ya. Tochitsky\textsuperscript{1}, P. Musumeci\textsuperscript{2}, C. E. Clayton\textsuperscript{1}, C. Pellegrini\textsuperscript{2}, J.B. Rosenzweig\textsuperscript{2} and C. Joshi\textsuperscript{1}

\textsuperscript{1}Department of Electrical Engineering, \textsuperscript{2}Department of Physics, University of California at Los Angeles, 405 Hilgard avenue, Los Angeles, CA 90025

Abstract An experiment on phase-locked injection of \textasciitilde100 fs electron bunches in a plasma beat wave accelerator is presented. We consider using an IFEL microbunching technique to produce ultrashort electron bunches prebunched at the exact wavelength of the plasma wave 340 \textmu m (\textasciitilde1THz). It is proposed to generate 100 MW of 1 THz radiation by difference frequency generation in a nonlinear crystal, mixing the same two CO\textsubscript{2} lines as used to drive the plasma accelerator.

INTRODUCTION

Laser -Plasma acceleration of particles is utilizing a relativistic plasma wave driven by a high-power laser beam. Plasma wave allows to couple energy of a transverse electromagnetic wave of laser field into a longitudinal electric field of the wave, thus making acceleration possible. The acceleration gradient has reached in experiments values from 3 to 100 GeV/m for the plasma density \(n_0\) \(10^{16}\) cm\(^{-3}\) and \(10^{19}\) cm\(^{-3}\), respectively \[1\]. So far all schemes of high gradient acceleration have shown 100 % energy spread. This is physically due to the experimental difficulties related to the generation and the injection of an electron beam in the high gradient accelerating field wave with a typical period of 10-300 \textmu m. It is obvious that if the injected electron beam samples all the phases of the accelerating field, the energy spectrum at the output will be continuous. The goal of second generation experiments is to reduce the energy spread to make an electron beam produced by a plasma accelerator usable for different applications.

There are two principle approaches to tackle this problem: optical injection of electrons in the plasma wave and injection of prebunched electrons in a plasma accelerator. For a \(10^{19}\) cm\(^{-3}\) plasma density, which corresponds to a plasma wavelength 10 \textmu m, perhaps the only way for a phased injection is production and injection of ultrashort electron bunches using different all-optical injection schemes:
LILAC, LIPA, colliding beams (see these proceedings for more information). However, for lower plasma densities and, therefore, longer plasma wavelength it becomes possible to produce a high quality electron bunch (bunches) with a duration short compared to the plasma wavelength. Injection of prebunched electrons that are synchronized to the high gradient electric field wave is commonly called phase locking. Several methods have been considered for injection of a phase-locked e-beam in a plasma accelerating structure [2]. However this has not yet been experimentally demonstrated.

In this paper we describe an experiment on phase-locked injection of ~100 fs electron bunches in a plasma beat wave accelerator proposed at Neptune Laboratory (UCLA). It is suggested to use an IFEL technique to produce ultrashort electron bunches prebunched at the exact wavelength of the plasma wave. For Neptune plasma accelerator the plasma wavelength is 340 μm (~1THz). We propose to generate 100 MW of 1 THz radiation by difference frequency generation (DFG) in a nonlinear crystal, mixing two CO2 lines. Co-propagating the radiation with the electron beam inside a short undulator achieves the bunching at the required wavelength. Moreover, because the electromagnetic radiation is generated from the same laser that excites the relativistic plasma wave, phase-locking could be achieved. In the first part of the paper we describe the scheme and report preliminary experimental results on generation of THz radiation using noncollinear DFG in GaAs. Then we present results of modelling IFEL microbunching and address a beam loading problem.

**EXPERIMENT ON INJECTION OF PREBUNCHEDED ELECTRONS**

The Neptune Laboratory at UCLA is being used to explore advanced accelerator concepts including Plasma Beat Wave Acceleration (PBWA) of electrons. Here a plasma beatwave with acceleration gradient 1-3 GeV/m is driven by a 100 ps two-wavelength TW CO2 laser pulse at 10.6 and 10.3μm [3]. For PBWA, electrons from a photoinjector are injected in a plasma accelerating structure. The injected electron beam comes from an RF gun followed by a linac which can produce up to 0.5 nC in several ps at 12 MeV [4]. At present the PBWA experiment is operating and a long (>340 μm) electron bunch is injected in the plasma structure and accelerated with 100 % energy spread. Production of the monoenergetic beam require a bunch length of about 40 μm.

In Fig.1 we show a proposed scheme for phase-locked injection of electrons in the plasma beat wave accelerator. As shown in the picture, a high-power CO2 laser beam is focused by a F/5-F/18 optic at the interaction point (IP) and drives the relativistic plasma beatwave. A small fraction (~ 4%) of two-wavelength CO2 laser radiation is splitted by a NaCl beamsplitter, and then sent onto a nonlinear crystal. Here, by difference frequency generation, as discussed in the next section of this paper, we should generate up to 100 MW of 1 THz radiation. This 340 μm wave originates from the mixing of the same two wavelengths that drive the plasma beat wave, so that it
has a well-defined phase relationship with the accelerating structure. The THz beam is made collinear with the electron beam and is sent through a planar undulator using a mirror with a hole. This off-axis parabolic mirror has also the function of focusing THz radiation to a spot size of 7 mm located at the end of a 0.5 m long undulator. As a result of the IFEL interaction the electron beam propagating through the undulator magnetic field is microbunched on the scale of 340 μm; then it is focused with the final focus triplet at the IP and finally it is accelerated by the relativistic plasma beatwave. Absolute phase between electrons and the plasma wave can be adjusted simply by using a delay line. The distance between the end of the undulator and the IP is up to 2 m. There is a possibility that debunching effects, taking place in the transport between the THz prebuncher and the plasma, will cause bunch lengthening. This issue is ought to be studied experimentally. Note that in the successful STELLA experiment where tolerances are tighter because of the shorter wavelength (10 μm), the IFEL accelerator was located 2.3 m downstream of the IFEL prebuncher [5].

**HIGH-POWER SOURCE OF THz RADIATION**

The key element of a laser-driven IFEL prebuncher is a powerful source of optical radiation. We propose to use difference frequency mixing process in a nonlinear crystal to produce high-power driving THz radiation (>100 MW) for the IFEL buncher. It is known that low DFG efficiency is a serious problem for the FIR
spectral range. The highest FIR power generated by now using this method is a few kW [6]. At the same time 100 ps, two-wavelength CO₂ laser pulses from the Neptune Lab system are naturally very well suited for producing high-power FIR radiation. Nonlinear frequency conversion efficiency increases significantly for short pulses: first owing to the power increase and second, this power can be coupled into a crystal because of the higher surface damage threshold for shorter pulses. According to the Manley-Rowe relations, the maximum power conversion efficiency can reach 3% for TW 10 µm pulses.

Three methods to generate high-power 340 µm radiation by CO₂ laser difference frequency mixing in a nonlinear crystal have been considered. They are: standard birefringent phase matching, quasi-phase matching with periodic structures, and noncollinear phase matching in isotropic materials. A comparative analysis shown that the later has the highest potential for FIR DFG [7]. Noncollinear mixing of two laser beams is possible in any crystal which possesses anomalous dispersion between the incident CO₂ laser radiation and FIR difference frequency radiation. Zernike [8] and Aggarwal et al. [9] have demonstrated noncollinear mixing of two CO₂ laser beams in liquid helium cooled InSb and GaAs samples. Several reasons make GaAs a good candidate for generation of high-power 340 µm radiation. It has a relatively high value for the electro-optic nonlinear coefficient d=43 pm/V. GaAs with high resistivity (> 10⁸ Ωcm) is transparent in the FIR beyond 200 µm at room temperature as well as in the 10 µm region of the CO₂ laser [10]. High-quality, single crystals with a diameter of 15 cm and length up to 10 cm are commercially available. The expected surface damage threshold could reach 10 GW/cm² for 100 ps CO₂ laser pulses.

For noncollinear phase-matched mixing of two laser lines of frequencies ω₁ and ω₂ (ω₁>ω₂) to generate the difference-frequency radiation at ω₃, the conditions of photon energy and momentum conservation require that

\[ ω_3 = ω_1 - ω_2 \]
\[ k_3 = k_1 - k_2 \]

where \( k_1, k_2 \) and \( k_3 \) are the respective vectors for radiation of frequencies \( ω_1 (10.3 \mu m), \ ω_2 (10.6 \mu m), \ ω_3 (340 \mu m) \). Fig 2a. shows the direction of propagation of the incident beams and that of the difference frequency radiation inside the crystal. Refractive indices for insulating GaAs are \( n_1=n_2=3.28 \) at 10 µm region, and \( n_3=3.61 \) at 340 µm [10]. According to Aggarwal et al. [9], for these values of refractive index we obtain \( Θ=0.72° \) and \( φ=21.64° \). The corresponding external phase-matching angle is 2.38 degrees. The angle at which FIR radiation propagates inside the crystal is greater than the critical angle for total internal reflection. Therefore, as it shown in Fig.2b, the output face of the GaAs crystal has to be cut at 21 degrees to release the newborn radiation.

Preliminary measurements of the DFG efficiency were done with a 3 cm long sample of (111) oriented GaAs. The measurements were performed with a two-wavelength output of a CO₂ master oscillator which provided 50 mJ in a 200 ns pulse. Fig. 2b
presents a schematic diagram of the experiment. The laser beam was compressed to a spot size of 1 mm in order to increase the conversion efficiency. By adjusting the distance between a ZnSe beamsplitter and a mirror we set the angle necessary for

FIGURE 2. Schematic wave vector diagram for noncollinear DFG (a) and optical scheme of an experimental set up for FIR DFG in GaAs (b).

produced was detected by a Gollay cell. The interaction length is limited by the length over which two crossed beams are overlapped and, according to calculations, was approximately 12 mm. We have observed FIR pulses with peak output power $P_{340}=100$ mW at peak input power $P_{10.3}=20$ kW and $P_{10.6}=80$ kW. It corresponds to a $10^{-6}$ conversion efficiency value. In order to compare the experimentally observed FIR power output with that expected from theory we used the following formula:

$$P_{\text{FIR}} = 0.5 \left( \frac{\mu_0}{\varepsilon_0} \right)^{0.5} \left( \frac{4d_{\text{eff}}^2 \omega_{\text{FIR}}^2}{n_1 n_2 n_3 c^2} \right) \frac{P_{10.3} P_{10.6} L_{\text{eff}}^2 T_1 T_2 T_3}{S} e^{-\alpha L_{\text{eff}}} \tag{2}$$

where $S$ denotes the area of the input beams, $T_1$, $T_2$ and $T_3$ are the single surface transmission coefficients at the frequencies $\omega_1$, $\omega_2$, and $\omega_3$ and $\alpha$ is the absorption coefficient of FIR radiation in GaAs. Theory predicts $P_{340}=212$ mW using $d_{\text{eff}}=50$ pm/V and the only available in literature absorption coefficient for THz radiation at room temperature of 0.2 cm$^{-1}$. This is in a reasonable agreement with the observed value (unknown absorption may be a possible reason for this discrepancy), and allows us to estimate possible FIR power for amplified pulses. Calculations have shown (see Fig. 3) that with the pump intensity of 2-4 GW/cm$^2$ and $L_{\text{eff}}=2.5$ cm one can expect growth of the conversion efficiency up to $4 \times 10^3$. It means that for 100 ps pump
pulses the 100 MW level of power could be achieved for a beam diameter of 5 cm (8-10 MW/cm² of the THz power density).

![Graph showing measured and calculated power at 340 μm as a function of pump intensity.]

**FIGURE 3.** Measured and calculated power at 340 μm as a function of pump intensity.

Due to high nonlinearity of GaAs interaction of a 10 μm beam of GW power with the nonlinear material may result in spectral broadening, amplitude modulation, etc. [11] which could limit the allowed pump power besides the damage threshold. Moreover frequency mixing of different spectral components of a broadened pump pulse can cause generation of 3-5 mm radiation in a collinear geometry. A detailed experimental study of these issues is required.

It is interesting that FIR power level could be scalable beyond 100 MW by increasing the beam diameter. A typical beam diameter of the Neptune TW two-wavelength CO₂ laser system is 12 cm with an intensity 10 GW/cm². This beam, in combination with available large-aperture GaAs crystals, opens possibility to create a unique high-power ≥1 GW source of coherent radiation in the range of 100 μm — 10 mm (0.03 -3 THz) on the base of noncollinear frequency mixing of CO₂ laser lines.
MODELLING OF IFEL BUNCHING

It is known that an IFEL acts as a longitudinal lens and microbunches the electrons on the scale of the electromagnetic wavelength [12]. At the Neptune Laboratory, in order to achieve efficient microbunching in the small experimental area available, we need to optimize the IFEL parameters. Optimization was done using standard equations of the motion for a single electron moving in a plane linearly polarized electromagnetic wave in a planar undulator field [13]. For 100 MW of THz radiation and a magnetic field of 0.25 T, we achieve maximum bunching through the Inverse Free Electron Laser interaction after 0.5m. It is important that having more electromagnetic power or a longer undulator doesn’t increase the performance of the system, the efficiency of the IFEL buncher reaches a limit due to the effects of the non-linearities and the longitudinal emittance dilution. Detailed results of optimization are presented elsewhere [7]. Parameters of a permanent magnet undulator are listed in Table 1.

Table 1. Undulator parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field</td>
<td>0.6 T</td>
</tr>
<tr>
<td>Undulator wavelength</td>
<td>10 cm</td>
</tr>
<tr>
<td>Magnet gap</td>
<td>2 cm</td>
</tr>
<tr>
<td>K parameter</td>
<td>2.2</td>
</tr>
<tr>
<td>Undulator length</td>
<td>0.5 m</td>
</tr>
</tbody>
</table>

Simulations confirm well our estimates. The results are shown in fig. 4. The simulations are performed using TREDI [14], a 3d Lienerd-Wiechert based, 4th order Runge Kutta, Lorentz solver code to track the electrons through the undulator magnetic field and the laser field. The input electron beam has the parameters typically running at Neptune laboratory, 4 ps long, 6 mm-mrad, 300 pC. The radiation is assumed to be a 100 MW THz wave, focused in vacuum to a 7 mm focal spot. In Fig.4a there is a snapshot of the electron longitudinal phase space at the end of the

FIGURE 4. Simulation results for THz IFEL microbunching.

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undulator. The longitudinal microbunches on the scale of the plasma wavelength are evident within the 4 ps (rms) long beam envelope. Fig. 4b shows the phase histogram over the 340 μm wavelength. The microbunches have a width of ~ 30 μm that is small (1/10) compared to the plasma beat-wavelength. Since THz radiation driving the IFEL is locked in phase with the plasma beatwave, all these microbunches are phase-locked with the accelerating structure. It is clear that for PBWA getting more electrons with a smaller phase spread will result in less energy spread after the plasma acceleration. At the same time the longitudinal emittance dilution caused by the nonlinearities is a principal limitation of the IFEL microbuncher.

Further improvement in this respect could be achieved by driving the same undulator with both 340 μm radiation and its 3rd harmonic as suggested recently by X.J. Wang for a 1 μm IFEL buncher [15]. As oppose to the 1 μm beam, it is not durable to generate the 3rd harmonic of THz radiation. However one can generate 114 μm radiation by noncollinear DFG in GaAs using CO₂ laser lines. In fact, if we take the 10.6 μm line -the same as for the beatwave, then the 9.7 μm line (the 9P(36) line) will provide the difference frequency equal to the 3rd harmonic of beatwave with a negligible frequency off-set of ~1 GHz. In experiment another laser beam from a MW power, 200 ns CO₂ laser could be used as a seed at 9.7 μm in combination with a TW 100 ps pulse at 10.6 μm. 3D modelling have indicated that indeed by choosing an optimal ratio between 114 and 340 μm radiation (1.5/1) one can significantly increase number of electrons trapped in slightly shorter bunches (~20 μm). Preliminary results are shown in Fig. 5.

Figure 5. Simulation results for the 3rd harmonic THz IFEL microbunching.

BEAM LOADING IN A PLASMA ACCELERATOR

As was shown in the previous section THz IFEL microbunching can produce ~ 100 fs electron bunches, which is ten times shorter than the plasma wavelength. Here we
examine analytically how many particles could be loaded in a plasma beatwave
accelerator both longitudinally and transverse in order to obtain the small energy
spread $\Delta E/E \sim 0.1$. It is known that when the electron beam and the plasma wave are
much larger than $c/\alpha_p$, the beam-loading problem is approximately one-dimensional
[16]. This condition is true for $c/\alpha_p \approx 50 \mu m$ for the case when the CO$_2$ laser beam
diameter is 400 $\mu m$ (F/18 focusing).

Longitudinal beam loading is limited by a wakefield production and the maximum
number of beam electrons is given by

$$N_0 \equiv 5 \times 10^5 \varepsilon \sqrt{n_0 S}$$

(3)

where $\varepsilon$ is the normalized plasma wave amplitude and $S$ is the cross-sectional area
of the plasma wave. In our conditions, for 10% wave, $N_0$ equals to $6 \times 10^9$ electrons.
Therefore for $\Delta E/E \sim 0.1$ one can load up to $6 \times 10^9$ electrons or 10 pC charge without
significant dumping the plasma wave. In experiment we do not expect to exceed this
charge per bunch.

It is obvious that transverse variation of the longitudinal electric fields will result in
a difference in energy gained by electrons or large energy spread. Typical size of the
plasma wave seen in the 2D-PIC simulations is 170 $\mu m$ (FWHM) for the laser field
intensity $2 \times 10^{14}$ W/cm$^2$ [17]. Such an accelerating structure requires an e-beam size
$\sigma_{\text{rms}} \lesssim 30 \mu m$. This is approximately 3 times larger what the Neptune photoinjector can
provide at the moment and further work is needed to improve quality of the e-beam.

SUMMARY

THz driven IFEL microbunching is a promising scheme for a phase-locked
injection of bunched electrons in a plasma accelerator. It is shown that for the
Neptune PBWA experiment $\sim 100$ MW of 340 $\mu m$ radiation is required to drive a THz
buncher. Results of preliminary experiments on generation of THz radiation using
noncollinear frequency mixing of CO$_2$ laser lines in GaAs are presented.

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