

TUNABLE THz-PULSE-TRAIN PHOTOINJECTOR

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Abstract

A THz-pulse-train photoinjector is under construction at the High-energy Optics and Electronics (HOPE) Laboratory, National Tsinghua University, Taiwan. A beat-wave laser with full tunability in its THz beat frequency is employed to induce the emission of the THz electron pulses from the photoinjector. We show in our study that such a photoinjector is capable of generating periodically bunched MeV electrons with a bunching factor larger than 0.1 at THz frequencies for a total amount of 1 nC charges in a 10-ps time duration. In a linac following the electron gun, velocity bunching compresses the 10-ps pulse width by 20 times and thereby increase the bunching frequency by a factor of 20.

INTRODUCTION

In the past, many laboratories have demonstrated temporally compressed electron pulses by sending properly energy chirped electrons into a chicane magnet or alpha magnet [1]. Apart from the interest of generating a single short electron pulse, generation of a fast electron pulse train has recently attracted much attention for producing high-brightness electron radiation. For example, Neumann *et al.* generated 2-4 electron bunches with a sub-THz pulse rate by using a modulated laser beam to illuminate the photocathode of an electron gun [2]. Power *et al.* proposed the use of birefringence crystals to split the driver laser pulse of a photoinjector to induce the emission of a fast electron pulse train from a photocathode [3]. To generate a long pulse train and ease the pulse-rate tuning, here we propose a photoinjector driven by a tunable beat-wave laser.

Figure 1 illustrates the proposed THz-pulse-train (TPT) photoinjector. The TPT photoinjector consists of three major elements, a photocathode accelerator, an emittance compensating coil, and a beat-wave driver laser. The beat-wave laser generates a laser radiation containing the beating of two frequency components separated by THz frequencies. The two laser components are derived from mixing of two amplified diode lasers, one with a fixed frequency and one with a tunable frequency. The beat frequency of the laser and thus the electron pulse rate can be tuned by varying the frequency of the tunable diode laser relative to that of the fixed-frequency one. By using such a tuning scheme, the proposed TPT photoinjector has a pulse rate tuning range exceeding 10 THz [4]. The TPT photoinjector uses the laser beat pulses to induce the emission of a fast electron pulse train, which does not

add any energy spread like other schemes using magnetic components. In the following, we will present our simulation and theoretical study of the TPT photoinjector by taking a 1.6-cell S-band electron gun [5] as an example. The bunching factor is the key parameter describing how well an electron beam is bunched. We calculate in the following the bunching spectrum for the electrons from the TPT photoinjector subject to a typical setup of a photoinjector.

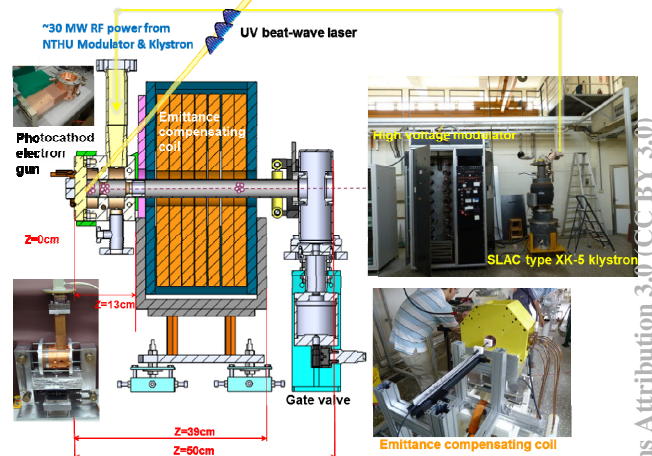


Figure 1: The proposed TPT photoinjector comprises a UV beat-wave laser, 1.6-cell S-band photocathode electron gun, and an emittance compensation coil. The beat pulses of the laser induce the emission of fast electron pulses from the photocathode of the electron gun.

TUNABLE BEAT-WAVE LASER

Figure 2 shows the design concept of the beat-wave laser driving the electron gun. The laser beat wave is combined from two diode lasers near 1.56 μm with their frequencies differing by THz. One diode laser has a fixed frequency and the other is fully tunable between 1.5 and 1.6 μm , corresponding to a tuning range of 12 THz. An optical parametric amplifier (OPA) pumped by a mode-locked Nd:YVO₄ laser boosts up the energy of the beat-wave seed to a kW-power level in a 10 ps pulse width. We then double the frequency of the amplified beat pulse near 1.5 μm to 780 nm in a second harmonic generator (SHG). The 780-nm beat-wave laser can be readily amplified in a Ti:sapphire laser amplifier. A third harmonic generator (THG) following the Ti:sapphire laser amplifier converts the amplified beat wave at 780 nm to UV to drive the photocathode electron gun.

If a broadband nonlinear laser amplifier is adopted in the pre-amplification stage, it is possible to generate a comb spectrum in the amplified laser pulse through cascading nonlinear frequency mixing. This comb spectrum, which is similar to that in a mode-locked laser, can be very useful in narrowing down each individual beat pulse in a laser pulse train, thereby decreasing the electron micro-bunch length from the TPT photoinjector. This comb-spectrum generation from an optical parametric amplifier was previously verified in one of our experiments [6]. The intensity envelope of the output laser pulse can be modeled as

$$I_e(t) = I_0 e^{-t^2 / (2\sigma_M^2)} \sum_{m=-\infty}^{\infty} e^{-(t-2m\pi/\omega_b)^2 / (2\sigma_\mu^2)} \quad (1)$$

where I_0 is the peak intensity, t is the time variable, σ_M is the rms width of the Gaussian pulse or the macro-pulse. For a Gaussian pulse with a nominal 10 ps full-width at half-maximum (FWHM), the rms pulse width of the Gaussian pulse is $\sigma_M = 4.25$ ps. The center laser frequency ω_c or the laser photon energy $\hbar\omega_c$ must be large enough to overcome the work function of the cathode material, where $\hbar = h/2\pi$, with h being the Planck's constant. σ_μ is the rms width of the beat pulse, and $\sigma_\mu \ll \sigma_M$ ensures many micro-pulses in a macro-pulse. The rms width of a beat pulse, σ_μ is proportional to the inverse of the overall width of the comb spectrum, σ_f .

The electron bunching factor is a figure of merit to describe how well an electron beam is bunched at a particular frequency. The bunching spectrum is defined as

$$B_f(\omega) = \left| \sum_{m=1}^N e^{i\omega t_m} \right| / N, \quad (2)$$

where N is the total number of particles, $j = \sqrt{-1}$ is the imaginary unit, and t_i is the temporal location of the i^{th} electrons. For a continuous distribution function of the electrons $f(t)$, Eq. (2) becomes a Fourier transform of $f(t)$, provided that the normalization $\int_{-\infty}^{\infty} f(f) dt = 1$ is applied.

Since the photoemission probability follows the low-frequency intensity envelope of the incident laser, the bunching factor at the cathode of the photoinjector is given by

$$B_f(\omega) = \left| \int_{-\infty}^{\infty} I_e(t) e^{i\omega t} dt \right| / \int_{-\infty}^{\infty} I_e(t) dt, \quad (3)$$

For the intensity envelope of the comb-frequency (comb-f) beat wave given in Eq. (1), by substituting Eq. (1) into Eq. (2), we derive the following bunching factor at the cathode:

$$B_f(\omega) = \frac{\omega_b \sqrt{\sigma_M^2 + \sigma_\mu^2} \sum_{m=-\infty}^{\infty} e^{-m^2 \sigma_\mu^2 \omega_b^2 / 2} \times e^{-\sigma_M^2 (\omega - m\omega_b)^2 / 2}}{\sqrt{2\pi} \sum_{m=-\infty}^{\infty} e^{-\frac{(2m\pi/\omega_b)^2}{2(\sigma_M^2 + \sigma_\mu^2)}}}, \quad (4)$$

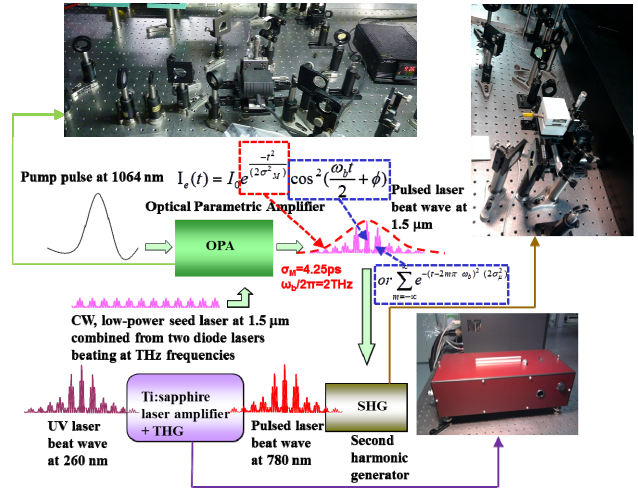


Figure 2: The proposed beat-wave laser system for driving the photoinjector.

TPT PHOTOINJECTOR

The particle acceleration process in a photoinjector could modify the initial particle distribution at the cathode and thus modify the bunching spectrum at the output of the accelerator. In this subsection, we present the simulated performance of the comb-f TPT photoinjector with a 100MV/m peak acceleration gradient by using the simulation code ASTRA [7]. The selected beat frequency for the driver laser is 2 THz. The initial electron pulses at the cathode follow the laser-intensity profile described by Eq. (1).

Fig. 3 shows (a) the solenoid field profile with a peak field of 2.66 kG at $z = 27$ cm, (b) the rms beam radius, (c) the normalized beam emittance, and (d) the energy spread versus distance for the pulse-train acceleration and propagation between the photocathode and the solenoid exit. The average output energy of the electrons is 4.6 MeV ($\gamma = 10$). It can be seen that, despite the use of the compensating coil, the emittance grows from 5 to 8.2π mm mrad due to the large space-charge force in the low-energy beam. The solenoid field was not fully optimized to reduce the emittance, but was used to provide a beam focus at $z = 50$ cm (the entrance of an undulator). The energy spread also increases slightly over z , again, due to the space-charge force.

The electron bunching can be quantitatively described by the bunching spectrum defined by Eq. (3). Fig. 4 shows the bunching spectra of the particles calculated at the cathode ($z = 0$), at the gun exit ($z = 12$ cm), and at the solenoid exit ($z = 50$ cm) for 1 nC charges, and at the solenoid exit for 0.1 nC charges. The initial bunching factor of 0.5 at 2 THz agrees well with the theory in Eq. (4). It can be seen from Fig 4 that the particle

acceleration process indeed lowers the bunching factor, and broadens the bunching spectrum for such a comb-f TPT photoinjector. The blue shift of the output bunching spectrum is due to velocity bunching during acceleration. The longitudinal pulse compression and thus the blue shift of the bunching spectrum are more evident for the 0.1 nC beam, in which the longitudinal space-charge force is smaller. For the 1 nC beam, it is interesting to note that the drift space between $z = 12$ cm and 50 cm helps to translate some energy modulation into a slightly higher bunching amplitude at 2.3 THz.

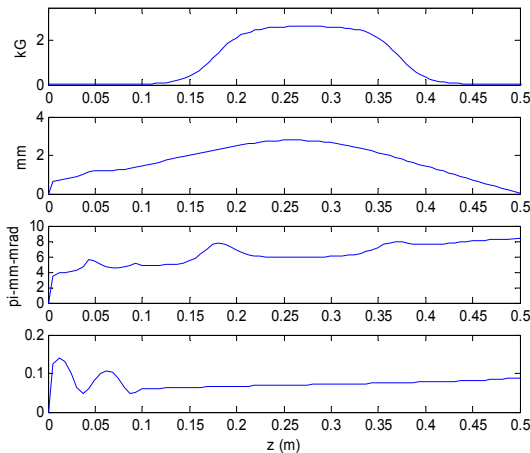


Figure 3: (a) Solenoid field, (b) rms beam radius, (c) normalized emittance, and (d) energy spread versus axial distance z for 2-THz electron pulses accelerated by a peak field gradient of 100 MV/m in the photoinjector.

Despite some debunching during acceleration and propagation, the bunching factor at the fundamental bunch frequency is still kept above 10% for 1 nC acceleration charges. The bunching factor of the 0.1 nC output beam is twice as large as that of the 1-nC output beam.

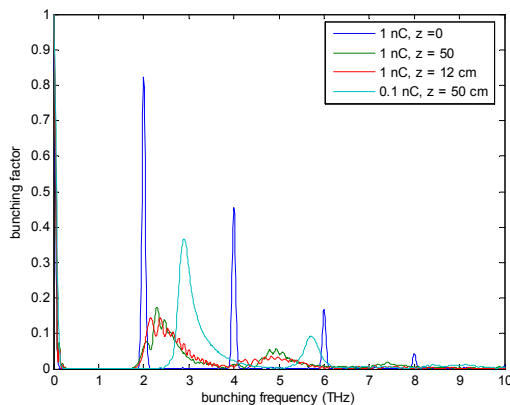


Figure 4. Bunching spectra for particles at $z = 0, 12$ cm, and 50 cm with 1-nC charges in the beam, and for particles at $z = 50$ cm with 0.1 nC in the beam. The micro-pulses are better retained in a low-charge beam.

CONCLUSION

We have also identified a highly effective and efficient tunable beat-wave laser system suitable for driving such a photoinjector. The laser beat pulses are generated by amplifying two low-power diode lasers beating at THz frequencies. Tuning the beat-pulse rate is achieved by varying the relative frequency between the diode lasers. We used the ASTRA code to model the performance of an S-band TPT photoinjector. In general, we found that a bunching factor larger than 0.1 is achievable at THz frequencies for 1 nC acceleration charges. The space-charge force plays a crucial role in degrading the micro-bunches during acceleration. With 10-times reduced acceleration charges, the bunching factor at the bunch frequency increases more than twice.

Velocity bunching in a photoinjector can increase the bunch frequency during particle acceleration. If a fixed pulse frequency at a radiation device is needed, this frequency change can be easily compensated for by varying the beat frequency of our tunable driver laser. The blue shift is sometimes desirable to multiply the bunching frequency of the electrons. In our preliminary study, we have seen a multiplication factor of 10 from velocity bunching in a linac following the electron gun for a 1nC pulse beam. Use of the pulse train from a TPT photoinjector to generate electron superradiance is presented in another paper (TUPA12).

ACKNOWLEDGMENTS

This work is supported by the National Science Council, under Contract NSC 99-2112-M-007 -013 -MY3. We appreciate Waikung Lau and An-Ping Lee of National Synchrotron Radiation Research Center help fabricate the photocathode electron gun.

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