BUNCHING-FREQUENCY MULTIPLICATION FOR A THz-PULSE-TRAIN PHOTOINJECTOR

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Abstract

A THz-pulse-train photoinjector employs a THz-pulse-train laser as its driver laser to generate an electron macro-pulse containing THz micro-bunches. We propose to compress the electron macro-pulse in a linac through velocity bunching to multiply its bunching frequency. Our study shows the bunching spectrum extends to a few tens of the harmonics of the initial micro-bunching frequency.

INTRODUCTION

A short electron pulse is desirable for generating high-brightness electron radiation or the so-called electron superradiance [1]. Apart from the interest of generating a single short electron pulse, generating a fast electron pulse train has recently attracted much attention for producing high-brightness narrow-line electron radiation. For example, Neumann *et al.* [2] produced 2-4 electron bunches with a sub-THz pulse rate by using a modulated laser beam to illuminate the photocathode of an electron gun. Power *et al.* [3] 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. Previously we have also proposed a fully tunable beat-wave-laser or THz-pulse-train (TPT) photoinjector [4], which generates THz electron pulses with a tunable pulse rate. However a laser frequency is on the order of a few hundred THz. It is not possible to generate a beam from the pulse-train photoinjector with a bunching frequency exceeding the laser's carrier frequency. In view of the strong demand for a compact *x*-ray free-electron laser (FEL), it is highly desirable to multiply the bunching frequency of the beam to the *x*-ray frequencies. In this paper, we propose to compress the electron macro-pulse from the TPT photoinjector as a way to multiply the bunching frequency of the electron beam. Electron pulse compression was mostly demonstrated with chicane magnets or an alpha magnet. To avoid coherent synchrotron radiation, we study in this paper electron pulse compression through velocity bunching in a traveling-wave linear accelerator (linac) following the TPT photoinjector. This scheme of pulse compression also avoids the need of the cumbersome magnets on the beam line.

Figure 1 illustrates the accelerator beam line in this study, wherein a TPT photoinjector, producing THz electron micro-pulses in a ~ps macro-pulse, is followed by a 3-m long SLAC-type traveling wave linac. The role of the linac is to provide velocity bunching to the electron macro-pulse generated from the TPT photoinjector. An array of solenoids in the beamline is to compensate emittance growth and confine the low-energy electron beam.

Throughout this paper, we used the space-charge tracking code, ASTRA [5], to study the particle acceleration and velocity bunching.

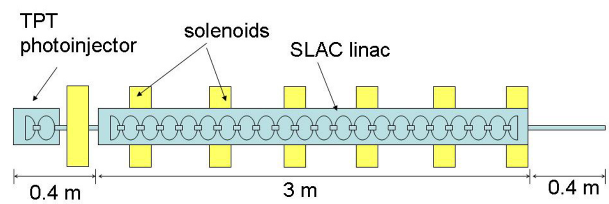

Figure 1: Schematic of the injector-linac configuration to study bunch-frequency multiplication for the beam from a TPT photoinjector.

TPT PHOTOINJECTOR

Figure 2 shows the scheme of the TPT photoinjector and some relevant photographs of the experimental setup.

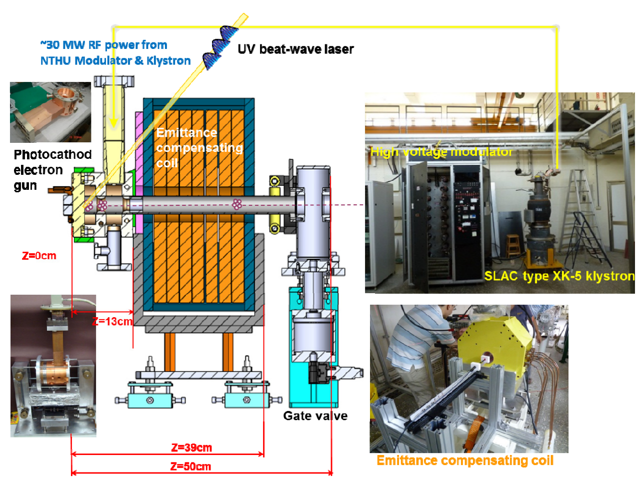

Figure 2: The TPT photoinjector comprises a TPT UV driver laser, 1.6-cell S-band photocathode electron gun, and an emittance compensation coil. The THz pulses of the laser induce the emission of fast electron pulses from the photocathode of the electron gun.

The TPT photoinjector consists of three major elements, a THz-pulse-train driver laser, a photocathode accelerator, and an emittance compensating coil. In our study, the photocathode accelerator is a typical S-band 1.6-cell photoinjector operating at 2.856 GHz [6]. The pulse rate of the emitted electrons follows the pulse rate of the driver laser. Varying the laser pulse rate can tune the electron's bunching frequency. This technique of generating a fast electron pulse train does not add any energy spread to the beam as do other schemes using energy modulators and chicane magnets.

In our study we first wrote a script in the MATLAB code to generate a distribution of 10^4 negatively charged particles at the cathode with a total charge of 30 pC. Refer to the particle histogram in Fig. 3(a). The particles are distributed inside a Gaussian macro-pulse envelope with an rms length of 4.25 ps or FWHM length of 10 ps. Inside the Gaussian macro-pulse, there are Gaussian micro-pulses with an rms width of 100 fs, repeating at 1 THz. Figure 3(b) shows the corresponding bunching spectrum at the cathode, indicating high harmonics up to 4 THz.

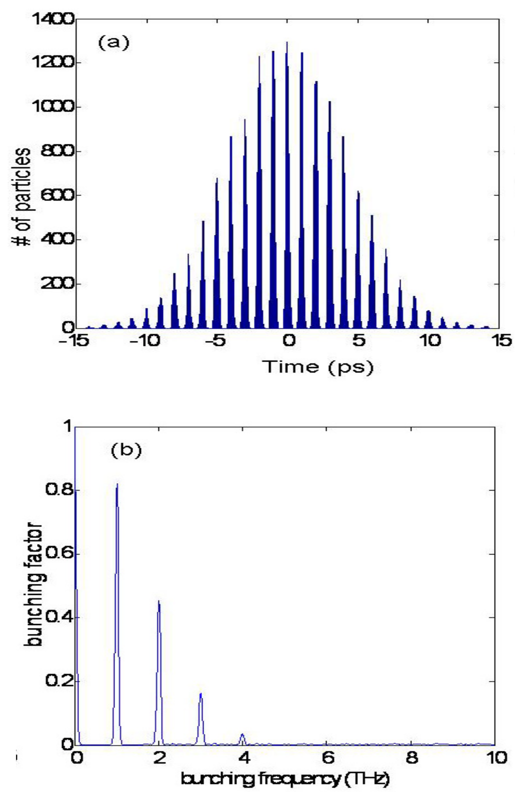

Figure 3: (a) At the photocathode, 1-THz Gaussian electron micro-pulses are distributed in a Gaussian electron macro-pulse. (b) The corresponding bunching spectrum indicates harmonics of the fundamental bunching frequency up to 4 THz.

Since the amount of charges is relatively small, in our simulation we set a radial distribution of particles with an rms beam radius of 0.3 mm at the photocathode. The small initial beam radius helps improve beam emittance. For what follows, the peak acceleration gradient of the photoinjector was set at 110 MV/m. The peak magnetic field of the compensating coil was set to 1.5 kG.

VELOCITY BUNCH

In our scheme, a 3-m long SLAC linac operating at 2.856 GHz is installed at z = 40 cm, immediately following the TPT photoinjector to provide macro-pulse compression through velocity bunching. Along the linac, we installed 5 solenoids with every adjacent two separated by 50 cm. The solenoids have a field profile the same as that of the emittance compensating coil. The first two solenoids have a peak magnetic field of 1.5 kG, and the rest three have a peak field of 5 kG.

To obtain efficient electron bunching, one would inject the leading edge of the electron bunch at the zero acceleration field of the linac to allow the whole bunch to slip backward toward the peak acceleration phase in the linac. The key is to extract the beam from the linac when the whole beam is bunched to the peak acceleration phase. In practice, the particle distribution in the longitudinal and transverse phase spaces at the output of the photoinjector also affects the velocity bunching in the linac. In our simulation study, we adopt an optimization sequence as follows. (1) With a peak acceleration gradient of 110 MV/m fixed for the photoinjector, we first set an acceleration phase for the photoinjector to obtain the best beam quality (energy, emittance, energy spread) at the output of the photoinjector, (2) we then scanned the acceleration phase and gradient of the linac to obtain the largest pulse compression ratio, and (3) we finally scan the acceleration phase of the photoinjector again to achieve the shortest possible macro-pulse length at the output of the beam line. Figure 4 shows the rms longitudinal beam size versus distance, indicating a result of 10-time compressed electron pulse at the output. The injection phases of the photoinjector and linac are 192 and 28°, respectively. The peak acceleration gradient in the linac is 5.9 MV/m.

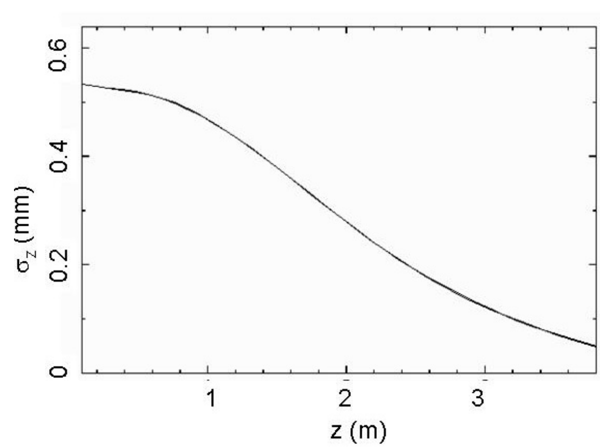

Figure 4: The rms longitudinal beam size at the output of the beam line is reduced by 10 times from the value at the cathode.

The corresponding output beam parameters from the ASTRA simulation are: normalized emittance = 3.8 mm-mrad, average beam energy = 8 MeV, rms beam radius = 0.2 mm, and energy spread 2.5%. The percentage energy spread can be reduced with further acceleration of the beam in subsequent linacs. For example, if the final electron energy is 200 MeV, the percentage energy spread is reduced to about 0.1%.

The 10-time reduction in the electron's rms longitudinal beam size does not mean a uniform pulse compression. The velocity bunching is a highly nonlinear process. Fig. 5(a) shows the histogram of the simulated particles in the time domain at the output of the beam line. It is seen that the pulse is compressed more on one edge than the other. One can also see the spiky distribution of particles, which is an indication of the increase of the bunching frequency due to velocity bunching. Figure 5(b) plots the bunching spectra at the cathode (blue line) and at the beam-line output (red line). It is evident that velocity bunching in the linac is extended the bunching spectrum to tens of harmonics of the input bunching frequency. For example, at the beam-line output, the bunching factors at 25 THz and 50 THz are clearly larger than 1%.

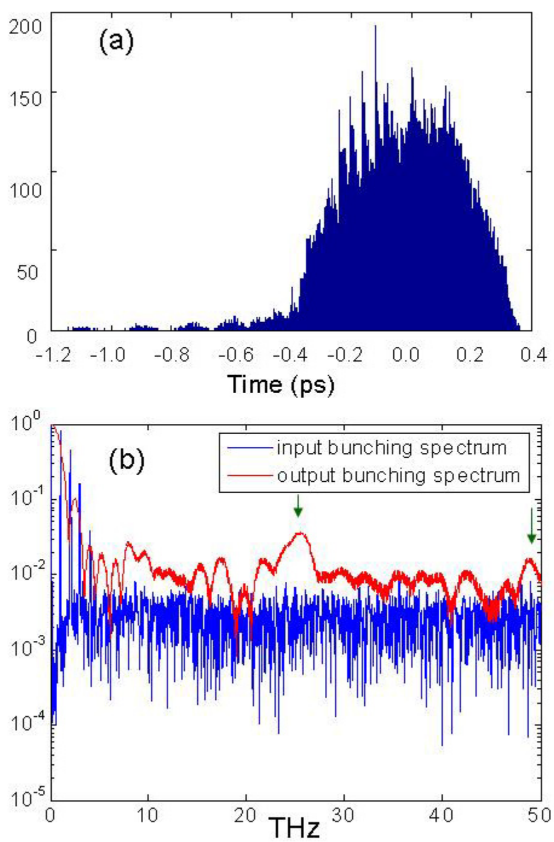

Figure 5: (a) Histogram of the particles at the beam-line output, indicating non-uniform pulse compression due to velocity bunching in the linac. (b) Comparison of the input and output bunching spectra at the photocathode (blue line) and at the end of the beam line (red line). The output bunching spectrum is extended over tens of the harmonics of the initial bunching frequency.

CONCLUSION

We have studied velocity bunching as a means to multiply the bunching frequency of a TPT photoinjector. Our study shows a multiplication factor of a few tens to the initial bunching frequency is possible by using a low gradient linac immediately following the TPT photoinjector. This bunching scheme does not need sets of chicane magnets and therefore does not induce coherent synchrotron radiation during the pulse compression process. We found from our study that the pulse compression ratio is sensitive to the amount of charges or the space charge force in the electron bunch. The initial beam emittance from the photoinjector can also affect the result of pulse compression. Different applications need different amounts of bunch charges. The beam emittance is also correlated with the amount of charges in the bunch. It is our next effort to find the limitation of this bunch-frequency multiplication technique in terms of the bunch charge and beam emittance.

ACKNOWLEDGMENTS

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