Experimental Observation of Energy Modulation in Electron Beams Passing through Terahertz Dielectric Wakefield Structures

S. Antipov,[1,3] C. Jing,[1,3] M. Fedurin,[2] W. Gai,[3] A. Kanareykin,[1] K. Kusche,[2] P. Schoessow,[1] V. Yakimenko,[2] and A. Zholents[4]

[1]*Euclid Techlabs LLC, Solon, Ohio 44139, USA*
[2]*Accelerator Test Facility, Brookhaven National Laboratory, Upton, New York 11973, USA*
[3]*High Energy Physics Division, Argonne National Laboratory, Lemont, Illinois 60439, USA*
[4]*Advanced Photon Source, Argonne National Laboratory, Lemont, Illinois 60439, USA*
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We report the observation of a strong wakefield induced energy modulation in an energy-chirped electron bunch passing through a dielectric-lined waveguide. This modulation can be effectively converted into a spatial modulation forming microbunches with a periodicity of 0.5–1 ps and, hence, capable of driving coherent terahertz radiation. The experimental results agree well with theoretical predictions.

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Free electron laser (FEL) based terahertz (THz) source technology is considerably attractive because of its capabilities for producing high peak power (beyond megawatts) at a high repetition rate (beyond megahertz) [1]. The key to generating coherent radiation in THz FELs is the formation of subpicosecond microbunches that are used to drive the THz radiation source. In the past decade, many approaches have been investigated to generate THz microbunches that include bunch generation from a photoinjector with microlaser pulses produced by birefringent crystals [2], bunch train with a picosecond separation using an emittance exchanger combined with transverse beam masking and other similar techniques [3,4], and some bunch compression techniques [5,6].

In this Letter, we report on the successful results of producing a strong energy modulation of an electron beam by means of the self-wake excited in a simple dielectric-lined waveguide. We used cylindrical geometry dielectric wakefield structures in this set of experiments. Alternatively, other geometries can be used, for example, rectangular or planar. Planar geometries with adjustable beam gaps for tuning the wakefield spectrum [7] can be used to produce tunable energy modulation. The energy modulation can be further transferred to density modulation by passing the beam through a chicane which is normally used for pulse compression of energy-chirped beams (for example, [6]). In this experiment, the energy modulation is produced by a THz structure; hence, subpicosecond bunch trains can be produced out of this beam utilizing only dipole magnets without further compression. The density modulated beam (a bunch train) can later be used as a drive beam for wakefield acceleration in THz structures [8] or for coherent emission of radiation [6,9,10]. It can be further compressed for applications in FELs and plasma wakefield acceleration [4,6,11]. This approach fills the niche between microbunching (a periodicity of a few microns) by inverse FEL acceleration [12–14] and bunching by laser pulse stacking for photoinjectors (millimeter periodicity) [2]. Similar microbunching can be achieved by masking the energy-chirped beam which travels through the dogleg. The mask is placed between the dipoles, in the region where the beam transverse size is dominated by the correlated energy spread [4]. This method has the disadvantage of partial beam loss at the mask.

The principle of introducing an energy modulation in the beam is rather simple. The self-wake in general reduces the beam quality: The transverse wake deflects the beam, and the longitudinal wake introduces an energy spread. However, when the bunch length is comparable to or much longer than the wavelength of the fundamental mode of the wakefield, the wakefield inside the bunch will show an amplitude modulation, particularly for a triangular or rectangular shaped bunch [15].

Intrinsically, without further corrections the electron bunch develops an energy chirp when it is accelerated in linacs. This energy chirp helps establish the energy bands around every amplitude cycle of the wakefield inside the bunch. Figure 1 shows an example of the theoretical process to form the energy modulation for a positive chirp (higher energy at the tail) triangular bunch. It should be pointed out that the conditions we imposed in this example are not strict at all. The energy chirp can have either positive or negative slope, and the bunch shape can be other shapes as well, like a long rectangular bunch which can be easily generated by using the laser stacking technique [2].

As shown in Fig. 1(a), a triangular shaped bunch has a current density distribution

$$I(t) = I_0\omega_0 t \quad \text{for } 0 < t < T \quad \text{and}$$
$$I(t) = 0 \text{ otherwise.} \tag{1}$$

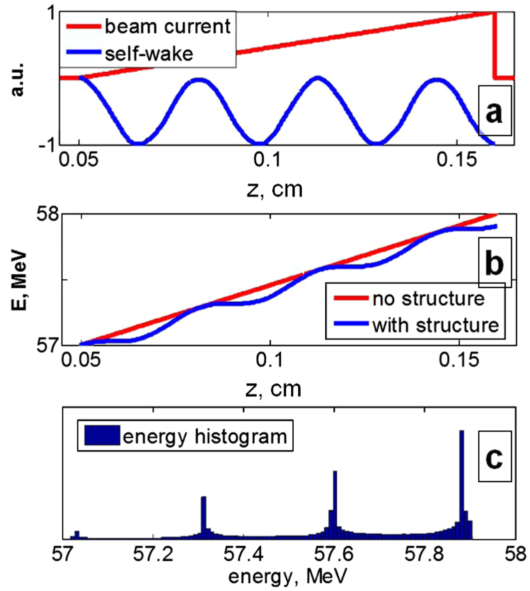

FIG. 1 (color online). (a) Beam current profile and self-induced wake inside the beam. (b) Energy—longitudinal coordinate distribution; original (red line) and modified due to self-deceleration (blue line). (c) Histogram of the self-energy-modulated beam.

Here I_0 is a constant, and ω_0 is the frequency of the lowest mode of the wakefield device. For simplicity, we consider a single mode wakefield structure for this argument, while the numerical model [Fig. 1] takes into account the first 8 higher order modes. The self-wake inside the drive bunch is [16]

$$V^{-}(t) = -\int_0^t 2kI_0\omega_0\tau\cos[\omega_0(t-\tau)]d\tau = -\frac{2kI_0}{\omega_0}(\cos\omega_0 t - 1), \quad (2)$$

which shows that the particles lose different energies in the wakefield device depending on their position in the bunch. Particles at nodes $t = \pi N/2\omega_0$ do not lose energy at all. If the bunch has a linear energy chirp at the entrance of the wakefield device, its longitudinal phase space will form a staircase shape [shown in Fig. 1(b)]: A strong energy modulation appears in the spectrum after the device [Fig. 1(c)], but its temporal profile is preserved for a relativistic beam.

The experiment was performed at the Accelerator Test facility at Brookhaven National Laboratory, which can provide an adjustable length shaped bunch with a linear energy chirp. For this experimental setup, a 130 pC beam with about 1.6 mm length was used. The beam energy is 57 MeV with 1 MeV energy chirp. The beam current is shaped by means of a mask inserted in a region of the beam line where the beam transverse size is dominated by the correlated energy spread [4,9]. The beam shaping mask was made in the form of an arrow: a triangular hole followed by a rectangular channel, which was originally designed for the requirements of another experiment [8]. In this experiment we were able to partially block the mask, producing beams ranging from 250 to 800 μm long triangular pulses and a 1.6 μm arrow shaped pulse. These dimensions were measured and calibrated by coherent transition radiation interferometry. Wavelengths longer than the beams are emitted coherently and carry information about the bunch length [17,18]. Transition radiation is sent to the interferometer, and the signal is recorded by a helium-cooled bolometer [4,9]. Because of the way the beam is shaped, there is a linear energy chirp from the head of the beam to its tail. In the energy dispersion-free beam line optics, this beam can be transported downstream to the spectrometer and maintain its "arrow" shape on the spectrometer screen [Fig. 2(a)].

In this experiment, we used three different quartz capillary tubes as wakefield structures. Each was metallized via gold sputtering on the outer surface and inserted into a stainless steel tube and then into a motorized holder. The dielectric constant of quartz is 3.8 over a broad range of frequencies including the THz range [19]. The dimensions of tubes and their synchronous TM_{01} mode frequencies are (1) 330 μm inner diameter (ID), 390 μm outer diameter (OD), 25.4 mm length, and 0.95 THz frequency; (2) 230 μm ID, 330 μm OD, 25.4 mm length, and 0.76 THz frequency; and (3) 450 μm ID, 550 μm OD, 51 mm length, and 0.615 THz frequency. The dimensions were measured by using a microscope. The thicknesses of the quartz tubes are small enough to diminish the effects of all high order modes.

The total arrow beam was 1.6 mm (0.8 mm triangle part and 0.8 mm rectangular part) long, much longer than the wavelength of three wakefield structures. The self-induced wake inside the arrow beam can modulate the energy producing as many "energy bunchlets" as there are wavelengths per total beam length. In Fig. 2, we observe energy

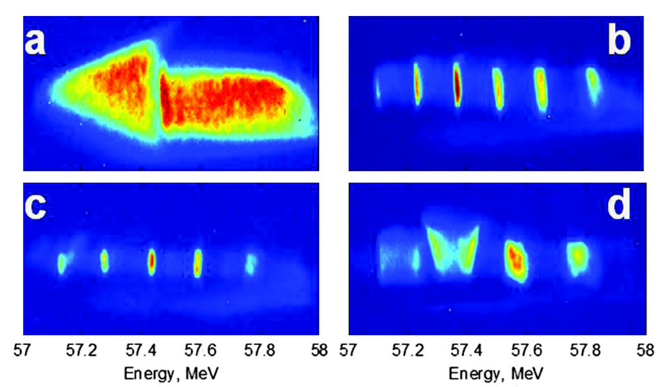

FIG. 2 (color online). Spectrometer images of the full-size 1.6 mm long arrow beam (triangle followed by rectangle). (a) Original, undisturbed beam. (b) Beam passing through the 0.95 THz structure. (c) Beam passing through the 0.76 THz structure. (d) Beam passing through the 0.615 THz structure.

modulation into 6 bunchlets using the 0.95 THz structure, 5 for 0.76 THz, and 4 for 0.615 THz. The features in the last case are particularly interesting: The first two energy bunchlets are split in two. This feature will be explained by a simpler measurement of a shorter triangular bunch.

If the length of the structure is longer than needed, then trailing particles in a bunch may be decelerated to a lower energy than the leading particle (for which the energy stays the same). In this case, we observe double bunches [Fig. 3(b)]. We observed this in the case of a 65 pC total charge, 800 μm triangular beam passing through a 25.4 mm long, 0.95 THz wakefield structure. First of all, the beam is about 3 wavelengths in size; hence, we see energy modulation into three energy bunchlets. Another way to observe it is to note in Fig. 3(c) that there are three locations in the triangular beam which do not experience the self-wakefield (the head of the triangle, $z \approx 0.05$ cm, $z \approx 0.082$ cm, and $z \approx 0.114$ cm). Because energies of particles at these locations are different, they will produce three energy bunchlets when other particles around them start experiencing deceleration and cluster around them. This example also shows the importance of the initial energy chirp for production of multiple energy bunchlets. If there were no chirp, particles at $z \approx 0.05$ cm, $z \approx 0.082$ cm, and $z \approx 0.114$ cm would have the same energy and location on the spectrometer. The observed three bunches will merge into one if the energy chirp is not present.

Comparing Fig. 1(b) to Fig. 3(c), the structure is longer than optimal for energy bunching (wakefield deceleration is too strong). This leads to the appearance of double bunches; see Figs. 3(b) (experiment) and 3(d) (simulation). Spectrometer resolution (estimated from the smallest energy spectrum image features at about 65 keV—FWHM) prevents us from observing sharp energy peaks, like in Fig. 3(d).

In the simulation [Fig. 3(c)] we observe that particles immediately following the leading particle are decelerated further below 57 MeV. Particles at $z \approx 0.082$ [Fig. 3(c)] do not experience deceleration; hence, they will form the second energy bunchlet. Particles immediately following them get decelerated to have energy less than the particles at $z \approx 0.082$. This forms the double bunching observed in the experiment [Fig. 3(b)]. Double bunching may not be an effective way to produce a modulated beam because of the loss after the chicane of particles that are not bunched. However, this allows for two bunches per wavelength for a particular structure and, hence, higher frequency bunching. In this case it is 6 bunches per 800 μm beam obtained in a 0.95 THz structure. When transferring this energy modulation into a density modulation, the chicane can correct or enhance some energy modulation features obtained by using the wakefield device. For example, three *double* bunchlets in the energy spectrum observed experimentally due to excessive deceleration in the wakefield device [Fig. 3(b)] can be transferred into three *single* bunches in density when using a chicane [20].

Finally, in beams smaller than a wavelength, only a single energy bunchlet is produced. Hence this approach can be used for reducing energy spread—a concept dubbed the "wakefield silencer" at the Argonne Wakefield Accelerator Facility [15]. At the Accelerator Test facility we used a 247 μm triangular beam with a 200 keV energy spread (FWHM) which was reduced by almost a factor of 3 to 70 keV by passing it through the 0.95 THz structure [Fig. 4]. In principle, by choosing a smaller size triangle, one can reduce the energy spread even further. However, the spectrometer resolution limit prevents us

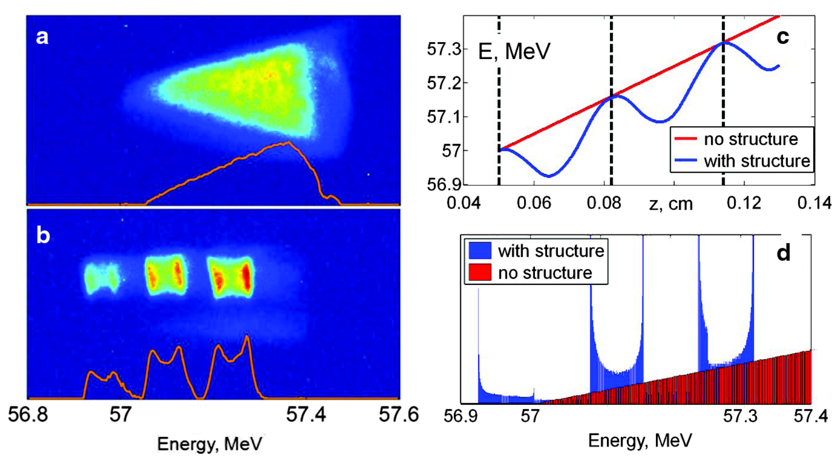

FIG. 3 (color online). (a) Spectrometer image and its projection of an unperturbed, 800 μm long beam. (b) Spectrometer image and its projection of the same beam that passed through the structure (measurement). Energy modulation is observed. (c) Simulated energy—longitudinal coordinate distribution; original (red line) and modified due to self-deceleration (blue line). (d) Simulated histogram of the original (red) and self-energy-modulated (blue) beams.

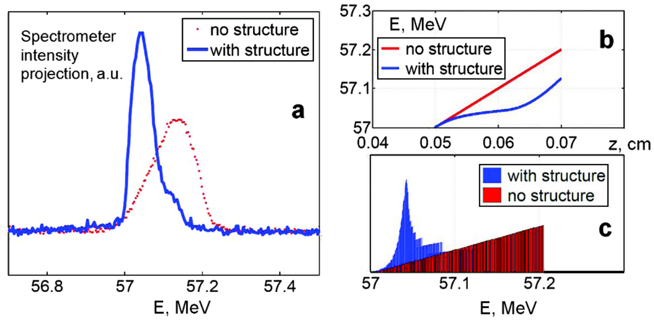

FIG. 4 (color online). (a) Spectrometer intensity projection (measurement) of original (red dotted line) and modified due to self-deceleration (blue solid line) beams. (b) Simulated energy—longitudinal coordinate distribution; original linear chirp (red line) and compressed due to self-deceleration (blue line). (c) Simulated histogram of the original (red) and self-compressed (blue) beams.

from observing a much narrower energy spread in this experiment.

For effective energy modulation, the structure length has to be chosen appropriately with respect to the beam charge (self-wake gradient) and the energy chirp to produce the case shown in Figs. 1(b) and 1(c) rather than Figs. 3(c) and 3(d). Identically, the total charge of the beam, with all the dimensions staying the same, can be adjusted for a particular structure length. This approach is more convenient in the actual experiment. The combination of beam charge, structure length, and initial energy spread can be packaged in a quantity that we term the "silencer strength" for the case of a short beam's energy spread reduction. We illustrate it in the following example. Wakefield silencing (reducing the energy spread by means of passive wakefield structure) can be utilized to reduce the energy spread of the FACET beam [21], which is almost 1 GeV. Considering the small dimensions of the FACET beam ($\sigma_z = 30\ \mu$m) any E-201 collaboration structure proposed for FACET studies [22] can be used as a silencer. Assuming that the FACET beam can be shaped to be a triangular beam, 30 μm long with 2 nC total charge, we will employ a multimode alumina structure with 508 μm ID and 790 μm OD. Such a beam will produce an almost linear [similar in shape to the area from $z = 0.05$ to $z = 0.055$ in Fig. 1(a)] decelerating field inside the triangle peaking at the tail with about 800 MV/m. This means that the original 1 GeV energy spread can be shrunk to 750 MeV by using a 25 cm long silencer. If the silencer strength is doubled (by length or total charge), the energy spread will be reduced to 500 MeV.

In the measurements reported here, we worked mostly with triangular beams. Energy modulation similar to the ones reported in this Letter can be produced in beams with other current distributions, like a rectangular bunch. For example, Fig. 2 shows that energy modulation was observed also in the rectangular part of the arrow beam.

In summary, this Letter demonstrated that an energy-chirped beam can experience a strong energy modulation by self-wake when passing through a passive wakefield structure. The number of energy bunchlets depends on the frequency of the wakefield structure, its length, and the beam's energy chirp and charge. Our numerical model accurately explains results including double bunching for the case when the wakefield structure length is not optimal for the beam. A beam with an initially flat energy distribution can be modulated only with two energy peaks (double bunching) with the modulation depth defined by the length of the structure and beam total charge. The energy modulation observed during the experiment can be effectively converted into a spatial modulation forming microbunches with a periodicity of 0.5–1 ps, capable of driving coherent THz radiation. This conversion can be done by a chicane allowing for additional tuning and correction of microbunching. Using a passive wakefield device together with a chicane is a simple and effective way of producing microbunched beams for beam-based high power THz sources. Utilization of tunable wakefield structures for both energy modulation and radiation allows for adjustable microbunching and, hence, tunable THz sources.

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