EXPERIMENTAL OBSERVATION OF ENERGY MODULATION IN ELECTRON BEAMS PASSING THROUGH TERAHERTZ DIELECTRIC WAKEFIELD STRUCTURES*

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Abstract

We report the observation of a strong wakefield induced energy modulation in an energy-chirped electron bunch passing through a terahertz dielectric-lined waveguide. This modulation can be effectively converted into a spatial modulation by means of a chicane, forming micro-bunches (density modulation) with a periodicity of 0.5 - 1 picosecond, hence capable of driving coherent THz radiation. The experimental results agree well with theoretical predictions.

INTRODUCTION

Free electron laser (FEL) based Terahertz (THz) source technology is considerably attractive because of its capabilities for producing high peak power (in the MW range) at a high repetition rate (>MHz) [1]. The key to generating coherent radiation in THz FELs is the formation of sub picosecond micro-bunches that are used to drive the THz radiation source. In the past decade, many approaches have been investigated to generate THz micro bunches that include: bunch generation from a photoinjector with micro laser 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 bunch compression techniques [5, 6].

In this paper, 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 [7]. We used cylindrical geometry dielectric wakefield structures in this set of experiments. Alternatively, other geometries can be used, for example rectangular / planar. Planar geometries with adjustable beam gaps for tuning the wakefield spectrum [8] 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 sub-picosecond 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 [9] or for coherent emission of radiation [6, 10, 11]. It can be further compressed for applications in FELs and plasma wakefield acceleration [4, 6, 12]. This approach fills the niche between microbunching (a periodicity of a few microns) by inverse FEL acceleration [12, 13, 14] and bunching by laser pulse stacking for photoinjectors (mm periodicity) [2].

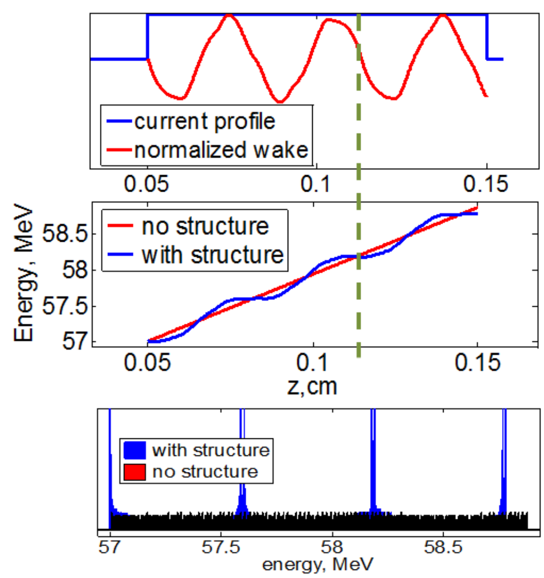

Figure 1: Top: beam current profile and self- induced wake inside the beam. Middle: energy – longitudinal coordinate distribution; original (red) and modified due to self-deceleration (blue). Bottom: histogram of the self-energy-modulated beam.

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 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] (Fig. 1). We also require the beam to have an energy chirp. For example, assume that the chirp is positive: the tail of the beam has higher energy than the head (Fig. 1, middle, red

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curve). There are locations within the rectangular bunch which experience no self-wakefield (Fig. 1, dashed line). Particles at these locations will preserve their energy as the beam travels through the wakefield device. Particles to the right of the "fixed energy" point have higher energy and will experience deceleration, while particles to the left have lower energy, but experience acceleration. The correlation of the energy spread becomes non-linear (Fig. 1, middle, blue). If the length of interaction is chosen appropriately particles in the beam will form energy bands (Fig. 1, bottom). Figure 2 shows the effects of the total wakefield device length (for a fixed charge, triangular current profile, and energy chirp of the beam) on the formation of energy modulation. In terms of energy the beam can be under-modulated, perfectly modulated and over-modulated.

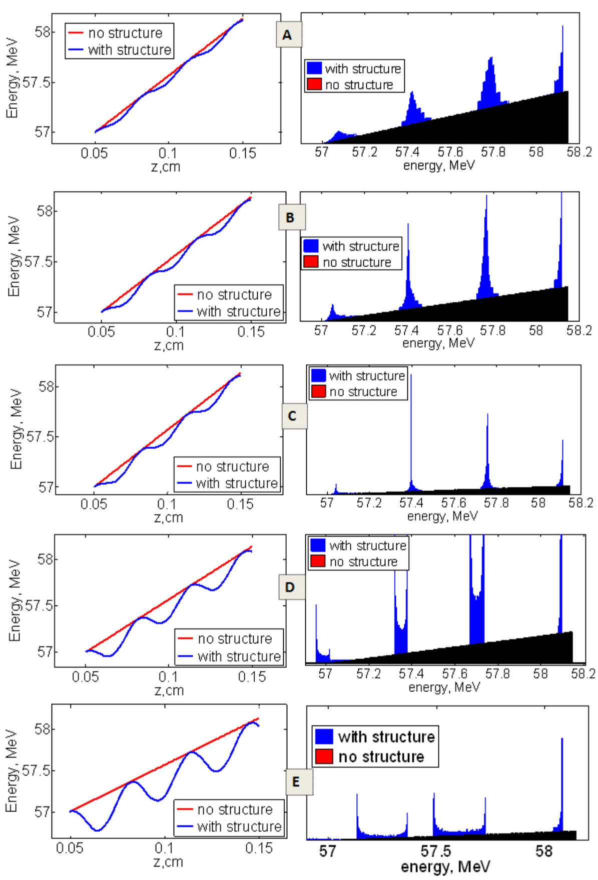

Figure 2: Energy modulation formation as a function of wakefield device length. Right side: red – original energy distribution vs. longitudinal coordinate, blue – energy distribution histogram after the structure. Left Side: same, phase space. A) Short wakefield structure. Energy bunching begins. B) longer structure. C) optimal length: perfect energy modulation. D) length over optimal: overbunching occurs. E) too long of a structure, double bunching occurs.

EXPERIMENT AT THE ATF

We performed the experiment at the Accelerator Test Facility, ATF (Brookhaven National Laboratory). This facility 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 a form of an arrow: a triangular hole followed by a rectangular channel, which was originally designed for the requirements of another experiment [8]. The full size "arrow" beam yielded total length of 1.6 mm, which was measured by coherent transition radiation (CTR) interferometry [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 beamline optics this beam can be transported downstream to the spectrometer and maintain its "arrow" shape on the spectrometer screen [Fig. 4 a)].

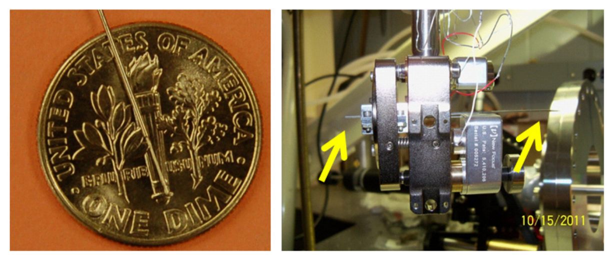

Figure 3: Left: photo of a quartz tube in a stainless steel housing, used as a wakefield structure in the experiment. Right: photo of a wakefield tube loaded in the motorized holder for beam alignment.

In this experiment we used three different quartz capillary tubes as wakefield structures (Fig. 3). 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 [16]. The dimensions and their synchronous TM_{01} mode frequencies (inner diameter, µm / outer diameter, µm / frequency, THz / length, mm) are: 1) 330 / 390 / 0.95 / 25.4; 2): 230 / 330 / 0.76 / 25.4; and 3): 450 / 550 / 0.615 / 51. The dimensions were measured using a microscope. The thicknesses of the quartz tubes are small enough to diminish the effects of all high order modes.

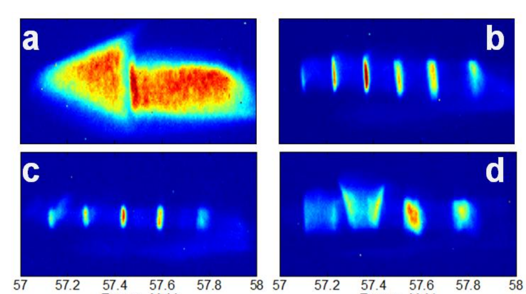

Figure 4: Spectrometer images of the full-size 1.6 mm long "arrow" beam (triangle followed by rectangle). a) original, undisturbed beam. b) Beam passing through 0.95 THz structure. c) Beam passing through 0.76 THz structure. d) beam passing through 0.615 THz structure.

The total “arrow” beam was 1.6 mm (0.8 mm – triangle part and 0.8 mm rectangular part) long; much longer than 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 in the total beam length. In Fig. 4, we observe energy 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 correspond to over-modulation in energy. The wakefield scales with the charge (current density). In the experiment we adjusted the charge to see the energy modulation on the spectrometer. The spectrometer resolution (estimated from the smallest energy spectrum image features at about 65 keV – full width at half maximum, FWHM) prevents us from observing sharp energy peaks, like in simulations with perfect energy modulation.

CONVERSION TO A BUNCHTRAIN

The energy modulation can be converted to a bunch train using a chicane. We present some simulation examples. For the 0.95 THz structure used in the experiment (Fig. 4) [7] R_{56} = 3 cm provides conversion to a bunch train (Fig. 5 a-c).

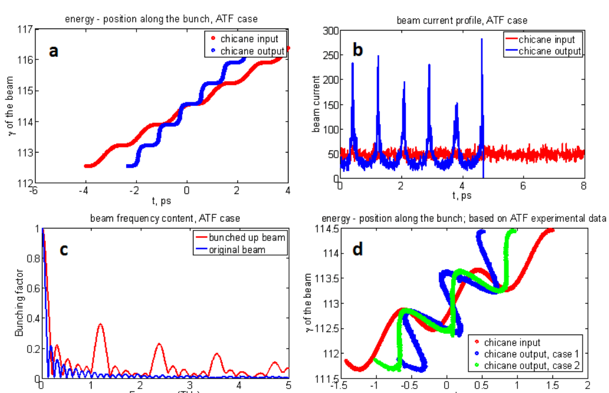

Figure 5: Energy modulation converted to a density modulation. a) energy – z phase space: before (red) vs after (blue); b) beam current: before (red) vs after (blue); c) beam frequency content: before (blue) vs after (red); d) example of chicane bunch train correction.

A two-step process of bunch train production consisting of energy modulation in a wakefield device followed by the chicane, has important tuning capabilities. If at the energy modulation step the beam was over-modulated energy-wise, this can be fixed by changing the dipole currents in chicane to yield larger R_{56}. This is depicted in Fig. 5, with the pre-chicane over-modulated energy – z phase space in red, output from chicane in its initial setting in blue and the corrected, stronger R_{56} chicane output in green showing perfect bunching. The initial energy chirp is not essential for bunch train production in this two-step process. The chirp was present in the experiment because it was essential for beam shaping. It was convenient for the spectrometer measurements. Without the energy chirp bunch train conversion produces frequency content corresponding to the wakefield device that produced the energy modulation. Adding chirp and adjusting the chicane for bunch train production out of a chirped beam yields frequencies up to two times higher, than the wakefield device frequency: a 100% tuning range!

In summary, our work demonstrates that an energy chirped beam can experience a strong energy modulation by its self-wake when passing through a passive wakefield structure. Our numerical model accurately explains the experimental results including double bunching for the case when the wakefield structure length is not optimal for the beam. We demonstrated that the energy modulation observed during the experiment can be effectively converted into a spatial modulation forming micro-bunches with subpicosecond periodicity, capable of driving coherent THz radiation. This conversion can be done by chicane allowing for additional tuning control and correction of micro bunching. Using a passive wakefield device together with a chicane is a simple and effective way of producing micro-bunched beams for beam based high power THz sources. Utilization of tunable wakefield structures for both energy modulation and radiation allows for adjustable micro-bunching and hence tunable THz sources.

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