SUBPICOSECOND BUNCH TRAIN PRODUCTION FOR HIGH POWER TUNABLE THZ SOURCE

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Abstract

An effective method of introducing an energy modulation in an electron bunch by passing it through a dielectric-lined waveguide was recently demonstrated [1]. In the follow up experiment we successfully converted this energy modulation into a density modulation by means of a chicane beamline. The density modulated beam was sent through a foil target, producing THz transition radiation which was characterized using interferometric techniques. By changing the initial energy chirp of the beam we tuned the center frequency of the generated THz radiation in the range 0.68 – 0.9 THz. A table top high power narrowband tunable THz source based on this technique is proposed.

INTRODUCTION

In recent years there has been a large interest in the production of sub-picosecond bunch trains consisting of series of equally spaced electron micro bunches [2-6]. These bunch trains can be used for production of high power THz radiation [4–6, and references therein] and to drive resonant wakefields in plasma and dielectric wakefield accelerators [2, 3].

Sub-picosecond bunch trains can be generated directly from a photocathode of an electron gun using a series of uniformly spaced laser pulses [6-8]. Alternatively, a transverse-to-longitudinal phase space exchange in combination with a multi-slit mask [9-12] can be used. Another approach is to use difference frequency generation by double energy modulation of electrons in an undulator via interaction with optical lasers having slightly different carrier frequencies [13, 14]. In this paper we present an approach using energy modulation by means of the self-excited wake fields in a dielectric-lined [1] or corrugated waveguide [15] with subsequent conversion into a sub-picosecond period density modulation.

A strong energy modulation in an electron bunch passing through a dielectric-lined waveguide was recently demonstrated in reference [1]. Here, we report the successful conversion of this energy modulation into a density modulation and production of a picosecond bunch train. This result provides a foundation for a compact, tunable source of intense THz radiation [RSI].

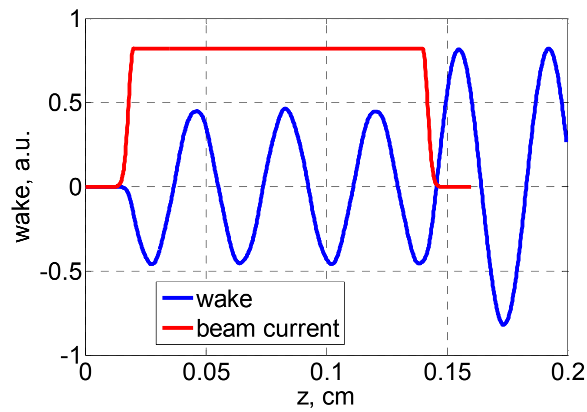

Figure 1: Periodic self-wakefield inside a long quasi-rectangular electron beam.

The principle of introducing an energy modulation in the beam is the following: 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 (Fig. 1). If the beam has an energy chirp (linear correlation between energy and longitudinal coordinate) then the periodic self-wakefield (Fig. 1) produces an energy modulation (Fig. 2). This energy modulation can be converted into density modulation by means of chicane, a set of four dipoles arranged in a "+ - - +" fashion. Inside the chicane high energy particles travel a shorter distance than those at low energies, hence sections of the beam in which low energy particles are ahead of the high energy ones will be compressed (Fig. 2). If the beam has a positive chirp (head having a lower energy than the tail) initially, the whole beam is compresed as well. Hence the current is modulated at a higher frequency than the frequency of the wakefield mode that created the energy modulation in the first place!

Changing the energy chirp of the beam therefore allows us to tune the frequency of the current modulation. In the case of negative chirp the resulting modulation will be at a frequency lower than the energy-modulating frequency of the wakefield. This property allows us to tune the frequency over a wide range.

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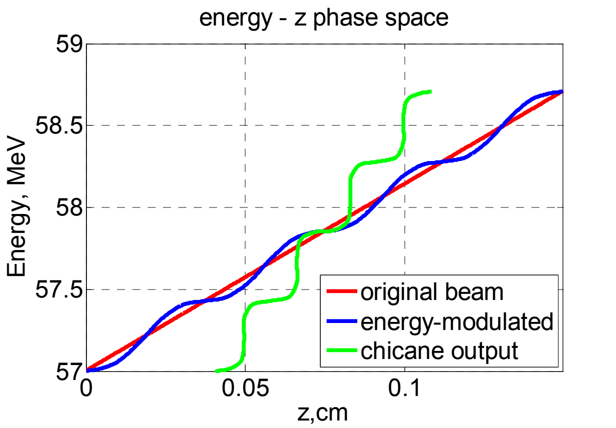

Figure 2: Illustration of the process of bunching and compression. Longitudinal phase space portraits for the incoming electron bunch (red), energy modulated bunch (blue) and density modulated bunch after the chicane (green).

If the original beam does not have an energy chirp (Fig. 3) then the current modulation after chicane is of the same frequency as the mode that created the energy modulation.

Chicanes are typically characterized by a so-called time-of-flight parameter, R_{56} (the transfer matrix element describing chicane's longitudinal dispersion). It relates the path length difference to the fractional energy offset [19] and has the units of cm.

$$\Delta\ell = R_{56}\left(\Delta E / E\right) \tag{1}$$

The time of flight parameter has to match the energy-longitudinal coordinate phase space to provide optimal compression. It is illustrated in Figure 3, where we plot the bunching factor b of an electron beam for various values of the chicane R_{56}.

$$b = \frac{1}{N}\sum_{i=1}^{N} e^{ikz} \tag{2}$$

While a time-of-flight parameter of 4.9 cm (Fig. 3) provides a density modulation of the beam, the corresponding bunching factor is on the order of 0.3. In contrast, R_{56} = 11 cm yields a maximum bunching factor of 0.5. These numbers, however, are rather large for practical realization. In the experiment we used a compact permanent magnet chicane with R_{56} = 1 cm. Even with a small time-of-flight parameter it is possible to have large bunching factors provided that initial beam is strongly modulated in energy prior entering the chicane [16].

EXPERIMENT

The experiment based on this concept was performed at the Accelerator Test Facility (ATF) at Brookhaven National Laboratory [16]. The electron bunches provided by the ATF beam line at 57 MeV had a rectangular peak current profile with a length of ~ 5 ps (1.5 mm) and amplitude of ~ 100 A. The current distribution is produced by passing the beam through two dispersive dipole magnets with a mask in between that cuts off the tails [10]. We can control the linear energy chirp along the electron bunch by changing the phase of the accelerating field in the linac. The head-to-tail energy variation was as large as 850 keV in the experiment, similar to the theoretical examples given previously. For a 1.5 mm long beam this would correspond to a chirp of 567 keV/mm.

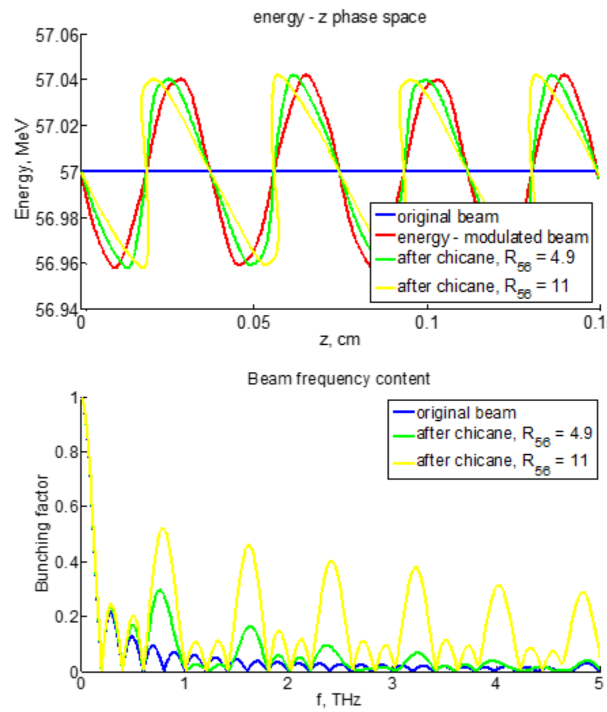

Figure 3: Bunching without compression. Top: Longitudinal phase space portraits for the incoming non-chirped electron bunch (blue), energy modulated bunch (red) and density modulated bunch after chicanes of different strengths (green and yellow). Bottom: frequency content of the beam. Initial beam (blue) and beam after chicanes of different strengths (green and yellow).

After acceleration, bunches were focused to a small transverse size (~ 100 μm rms) and transported through a 800 GHz, 2" long kapton (polyimide) tube, metallized on the outside and with a 300 micron inner radius and 28 micron wall thickness. The kapton has nearly constant permittivity ε in the range of frequencies between 0.5 THz and 1.5 THz. The chicane was made out of four identical permanent dipole magnets. Each magnet has 5 cm magnetic length and ~ 9.4 kG maximum magnetic field for a 5 mm magnetic gap. The distance between the first and the second magnet and the third and the fourth was 5 cm. This chicane had the matrix element value R_{56} =1 cm. We were able to move the chicane in and out of the beam line so that it was possible to measure the electron bunch properties both with and without the presence of the chicane. After the bunch passes through energy modulating structure and then through the chicane it becomes density modulated and this modulation can be measured by passing the bunch through a foil, producing coherent transition radiation (CTR).

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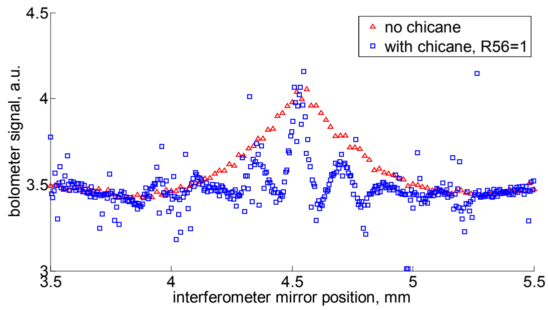

Figure 4: Measured THz CTR signal. Beam passing through chicane (blue rectangles) and chicane retracted (red triangles).

The time structure of the CTR signal is analyzed with a Michelson interferometer using a bolometer as the detector [9, 10]. The result of the interferometric measurement is the autocorrelation function (intensity as a function of the path length difference in the interferometer) of the CTR signal that has a periodicity related to the periodicity of electron bunch. The resulting bunching can be clearly observed through the periodicity of the autocorrelation function. Fig. 4 compares interferometric measurements of the original bunch (chicane retracted) and the density modulated bunch. The autocorrelation function is periodic for a signal produced by the density modulated beam, while the original long rectangular bunch does not produce periodicity over the distance spanned by interferometer mirror motion. We can also conclude that there are 4 beamlets in the density modulated beam (bunch train) because we have 7 pronounced peaks on the autocorrelation function plot. This determines that the bandwidth of the signal is about 25%. By changing the chirp of the beam we were able to tune the density modulation [16] over a range estimated at 0.68 to 0.9 THz.

Based on these encouraging results we have developed a concept for a beam based high peak power tunable THz source. All components are similar to those used in this experiment but adjusted to the specific needs of a dedicated THz radiation source. An electron bunch is produced in the gun and accelerated to a few MeV off-crest forming an energy chirp along the electron bunch. After that it passes through a dogleg (two dipole magnets of equal strength and opposite sign, Fig. 1) where a collimator is used to cut the bunch tails and to provide a uniform density distribution with a relatively sharp leading edge [10]. Next, similar to the experiment above this bunch traverses an energy modulating structure. The energy modulation acquired is converted into a density modulation in a chicane. The resulting bunch train is injected into the power extractor, which is essentially another wakefield producing structure, a dielectric loaded or corrugated metal waveguide equipped with a horn type antenna. Additional electron focusing optics may be needed to control the beam size as it loses energy in the extractor. For the 800 pC, 100 A, 57 MeV ATF beam we propose to use a 3 cm long quartz tube with ID = 0.3 mm and OD = 0.4 mm to produce a 0.7 THz, 170 ps long pulse with a peak power of 6 MW and 1 mJ energy per pulse.

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