THz Driven Accelerators and X-ray Sources

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Abstract: Approaches towards a linear THz accelerator technology are discussed. Theoretical and first experimental results on laser based high energy THz generation, guns, accelerators as well as compact X-ray sources based on these devices are presented.

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1. Introduction

Today, high brightness and highly relativistic electron beams are generated by circular or linear accelerators (LINAC) typically operating with 1-3 GHz accelerating frequencies and approaches towards X-band frequencies in the 10 GHz range are maturing. The achievable accelerating gradients are limited by field emission from cavity walls influenced by pulsed heating to several tens of MV/m in the case of low frequencies and up to 100 MV/m in the case of X-band frequencies. Short electron bunches are typically created by photoemission from the cathode in the presence of a strongly accelerating field followed by bunch compression. Low charge bunches, 1-10 pC, may be compressed to durations down to 3 – 10 μm (or 10 – 30 fs in pulse duration). At a given accelerating field strength and RF frequency, compression is limited by space charge. With higher operating frequency, higher gradients in the accelerating electric field arise which enhances velocity bunching and leads to the generation of shorter electron bunches. These short electron bunches can be used for ultrafast electron diffraction or intense X-ray production. Choosing an operating frequency of the accelerator in the THz range, i.e. here 0.1 - 0.5 THz and using multi-cycle to single-cycle pulses, accelerating fields in the 0.3 to 1 GV/m range are sustainable and bunch compression to the sub-femtosecond level of significant charge on the order of ~ 1 pC becomes possible. To drive electron guns and accelerators high-energy single-cycle and multi-cycle THz pulses in the mJ and tens of mJ range, respectively, are necessary. Here, we discuss approaches towards this goal and results achieved so far.

2. High energy THz generation

The traditional approach towards generation of single-cycle THz pulses is via optical rectification in Lithium Niobate using the tilted pulse front technique (TPFT) [1]. Using 1 micron, sub-ps pulses up to 0.4 mJ THz pulses have been generated with up to 0.8% efficiency albeit the center frequency moved below 0.2 THz, which would then need even higher THz energies as a driver, since corresponding structures are larger [2]. Here, we report generation of single-cycle THz pulses with a center frequency of 0.28 THz, an energy of 0.2 mJ and a conversion efficiency of 0.5% using 40-mJ, 1020-nm, 1-ps pulses from a cryogenic Yb:YLF laser generated with the TPFT method in cryogenically cooled Lithium Niobate. Numerical simulations show, that further scaling to 1% efficiency with 100 mJ driver pulses is possible and should result in 1 mJ THz pulses at about 0.3 THz wavelength. Cryogenic cooling of Lithium Niobate lowers the absorption at THz frequencies. The conversion efficiency is limited due to break-up of the driver pulses after excessive cascading [3].

For multi-cycle or narrowband THz generation, difference frequency generation (DFG) in cryogenically cooled periodically poled lithium niobate (PPLN) crystals using quasi-phase matching promises high conversion efficiency of several percent. Cryogenic cooling allows the use of long crystals and cascading does not lead to break-up of the driver pulses as in the TPFT case due to collinear interaction of the waves [4]. DFG using high-energy broadband Ti:Sapphire pulses and the chirp and delay method to match the difference frequency to the quasi-phase matching period resulted in 40 μJ pulses at 0.5 THz and 260 ps duration [5]. The use of large aperture crystals fabricated by the Taira group and linearization of the difference frequency between the chirped and delayed pulses lead to further improvements by more than an order of magnitude to produce 460 μJ of THz radiation with about 460 mJ of laser pulses [6]. The future goal is to generate with 5% conversion efficiency up to 50 mJ of multi-cycle THz pulses from 1-J laser pulses to drive a THz accelerator using dielectrically loaded metal waveguides [7].

3. THz guns and acceleration

Over the last years, demonstrations have shown the feasibility of a THz accelerator technology. A proof of principle THz acceleration experiment based on laser-generated single-cycle THz pulses with 10 μJ pulse energy at 0.45 THz has been performed recently [8]. First THz guns based on a parallel plate THz waveguide have been reported

producing quasi-monochromatic electron bunches with a few percent energy spread around 400 eV mean energy [9]. More advanced THz gun structures driven by either single-cycle or multi-cycle THz pulses have been proposed [10,11]. The single-cycle gun structure is a segmented THz waveguide device composed of arrays of parallel plate waveguides with dielectric fillings to delay the THz pulses in each waveguide, such that when excited with a single high energy THz pulse jointly, a tilted pulse front is created at the interaction point with electrons. This leads to

Fig. 1: (a) Acceleration of an electron bunch from a 55 keV DC-gun using a segmented THz waveguide acceleration device with dipole magnet for energy measurement on MCP; (b) electron energy spectrum without (black) and with THz pulse (red). [12]

continuous acceleration of the electron bunch in the interaction areas, see Fig. 1 (a). To demonstrate this single cycle accelerator concept, we used a UV-photo-triggered, 55 kV DC-gun to inject an electron bunch into the accelerating structure. The accelerating structure is driven by two single-cycle THz pulses with about 10 μJ of THz energy. Fig. 1 (b) shows the energy spectrum of the accelerated electron bunch, measured by a dipole magnet and an MCP. The spectrum measured with and without the THz pulses are shown. The THz accelerator boosts the average electron energy by 35 keV and significantly broadens the energy distribution due to the long electron bunch from the DC-gun of about 500 fs. The long pulse fills significant portion of the about 3 ps period accelerating THz field cycle. For acceleration, the two THz pulses are injected such that the electric fields constructively interfere in the center of the structure, and, in forward direction the transvers magnetic fields are canceled. If the pulses are delayed with respect to each other by half a THz wavelength, the electric fields cancel in the center of the device and the transvers magnetic fields add, which leads to a transvers deflection of the electron bunch.

This operation mode can be used for streaking of the electron bunch to measure its duration [12]. The deflection strength of about 140 $\mu\text{rad/fs}$ allows for sub-10 femtosecond resolution. The structure has been also used to demonstrate temporal pulse compression, focussing and defocussing with up to 2 kT/m focussing strength.

Current work is geared towards pushing laser based THz generation to the multi-mJ level using Joule level, picosecond laser pulses with optimized pulse formats [4]. Such high energy THz pulses can accelerate electrons to the 10-20 MeV level, energetic enough to enable in a first step hard X-ray generation via inverse Compton scattering [13].

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