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SEGMENTED TERAHERTZ DRIVEN DEVICE FOR ELECTRON ACCELERATION*

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Abstract

We present a staged Terahertz accelerator composed of a compressor and accelerator stage. Preliminary experiments are described demonstrating >30 keV energy gain and compression of electrons down to 100 fs for 55 keV electron bunches from a DC-gun.

INTRODUCTION

Over the past decade, X-ray free-electron lasers have become an essential tool for the study of ultrafast phenomena with the atomic length scale and femtosecond time resolution. Radio-frequency technology has been the conventional technology for powering such facilities [1]. However, the costly infrastructure of large size and significant power consumption greatly limits it availability to the broad scientific community. The inherent difficulties in synchronization and low acceleration gradient limit its further development in pursuing even higher spatial and temporal resolution. Strong motivation thus exists for exploring alternative technologies of diminishing their size and cost adapted for pushing the resolution frontier especially where lower levels of charge in the sub-pC range is sufficient. Among such alternative sources, Terahertz-driven accelerators are currently under intense investigation as a potential alternative approach [2,3,4] with the promise to overcome both the limitations of radio-frequency acceleration and the challenges in other compact accelerators, such as fabrication tolerances in dielectric laser accelerators (DLAs) [5,6] and instabilities and difficulties in controlling injection in laser-plasma accelerators [7]. The picosecond period fields make terahertz sources suitable to capture and control ultrafast electron pulses with moderate charge (pC) and femtosecond precision. Ultrafast terahertz pulse sources with GV/m [8,9] electric field strengths have been generating, which are one to two orders of magnitude higher than the fields in state-of-the-art radio-frequency accelerator systems. This may allow to shrink km conventional accelerators to the tens of meter-scale. Proof-of-principle demonstrations have showed multi-keV acceleration, as well as manipulating of electrons with Terahertz radiation [4,10]. Very recently, we demonstrated a Segmented Terahertz driven Electron Accelerator and Manipulator (STEAM) device [4] that has shown well controlled manipulation of electron bunches. It proves to be a very practical, compact Terahertz-based device which can support sufficient charge and high field gradients to realistically be used to boost performance of existing accelerators or function as a componentsof future compact accelerators.

In this work, we further explore the versatility of the STEAM device, by using it in two stages with different functions. In order to achieve high energy acceleration with narrow energy spread, a STEAM Buncher is used to compress the elctron bunch to 100 fs, which is followed by a STEAM LINAC to further accelerate the electron bunch.

THz ACCELERATION

Figure 1 shows the schematic view of the experimental setup with two photographs showing the STEAM Buncher and LINAC. 55 keV electron bunches are generated from a photo-triggered DC gun and injected into a Terahertz-powered STEAM device for compression. A second STEAM device is used as a Linac. All Terahertz devices are powered by the same infrared laser source. Ultraviolet pulses for photoemission were generated by two successive stages of second harmonic generation (SHG). The rest of the infrared laser was split into four and generates single-cycle Terahertz pulses by intra-band difference frequency generation. Each Terahertz pulse was coupled into the STEAM devices (Fig. 1) transversely by a designed horn structure which concentrated the Terahertz fields beyond the diffraction limit into the interaction zone. According to the Lorentz force law, the electrons experience both the electric and magnetic fields of the Terahertz pulses. The electric field is thus responsible for acceleration and deceleration, while the magnetic field induces transverse deflections. Inside the STEAM device, the Terahertz pulse is split transversely into a few sections with varying thickness (Fig.1) and guided into the interaction region by thin metal sheets, which ensure effective Terahertz electron interaction. Dielectric slabs of varying length were designed and inserted into each layer to control the arrival time of the Terahertz waveform to coincide with the arrival time of the electrons, effectively quasi-phase-matching the interaction. The electrons should arrive at the adjacent layer in the designed time to prevent dephasing.

Both of the two STEAM devices are operated in the "electric" mode [4], in which the fields are timed to produce electric-field superposition and magnetic-field cancellation at the interaction region. They were operated at two operation points:

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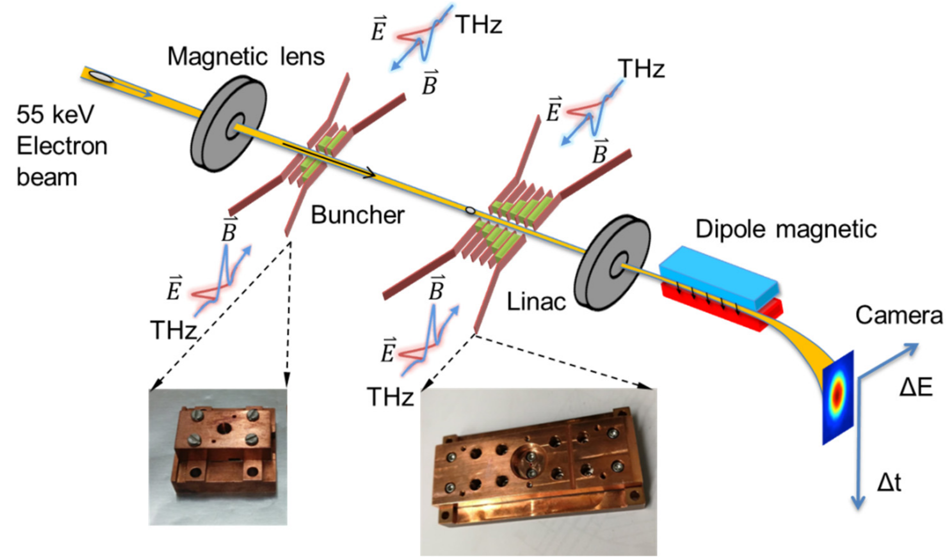

Figure 1: Acceleration of an electron bunch from a 55 keV DC-gun using a STEAM-Buncher and STEAM-LINAC followed by a dipole magnet for energy measurement on a MCP; Inset: STEAM Buncher (left) and STEAM LINAC (right).

• STEAM Buncher: The "compression" point, in which the electrons experience a zero-crossing of the Terahertz field and see symmetric acceleration and deceleration that enables a ballistic longitudinal focus inside the STEAM LINAC.

• STEAM LINAC: The "acceleration" point, in which the electrons only see the negative cycle of the Terahertz field.

The function of each STEAM device was selected by tuning the relative delay between the counter propagating Terahertz pulses and the electrons, which were controlled by means of motorized stages acting on the respective infrared pump beams. For electron bunch energy measurements, an electromagnetic dipole was used to induce energy-dependent deflections vertically and measured by the MCP-detector downstream. The compression was optimized by a STEAM streak camera [4] that was used at the position of the STEAM LINAC.

Preliminary experiments without the compressed electron bunch have shown that with around 2×6 μJ Terahertz, we are able to get more than 30 keV acceleration. The peak field inside the cavity is calculated to reach ~70 MV/m. A clean shift in energy spectrum is seen in Fig. 2 (a). However the accelerated electron beam has a very broad energy spectrum, which is mainly due to the long electron bunch from the DC gun. However, with the STEAM Buncher we are able to compress the electron bunch down to 100 fs at the injection point of the STEAM LINAC. Combined operation of both devices will greatly help to improve energy spread of the accelerated bunch, in forthcoming experients.

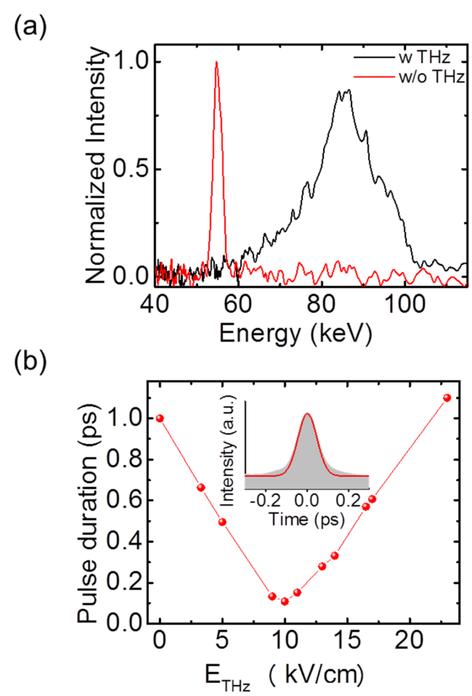

Figure 2: (a) Measured electron energy spectra for initial input beam (red curve) and accelerated beam (black curve) that shows an energy gain of more than 30 keV. (b) Measured electron bunch FWHM duration versus incident terahertz field strength (black squares) and corresponding simulation results (red line). Inset: the retrieved e-beam temporal profile.

CONCLUSION

We proposed multi-stage THz accelerator based on STEAM modules. It provides a practical multistage, monoenergetic Terahertz based accelerator.

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REFERENCES

[1] European X-Ray Free-Electron Laser Facility; http://www.xfel.eu/.

[2] A. Fallahi, M. Fakhari, A. Yahaghi, M. Arrieta and F. X. Kärtner, "Short electron bunch generation using single-cycle ultrafast electron guns", *Phys. Rev. Accelerators and Beams* 19, 081302, (2016).

[3] M. Fakhari, A. Fallahi and F. X. Kärtner, "THz cavities and injectors for compact electron acceleration using laser driven THz sources", *Phys. Rev. Accelerators and Beams* 20, 041302 (2017).

[4] D. Zhang, *et al.,* "Segmented terahertz electron accelerator and manipulator (STEAM)", *Nature Photonics* (2018), DOI: 10.1038/s41566-018-0138-z

[5] E. A. Peralta, *et al.,* "Demonstration of electron acceleration in a laser-driven dielectric microstructure", *Nature* 503, 91-94 (2013).

[6] J. Breuer and P. Hommelhoff "Laser-based acceleration of nonrelativistic electrons at a dielectric structure", *Phys. Rev. Lett.* 111, 134803 (2013).

[7] W. Leemans and E. Esarey "Laser-driven plasma-wave electron accelerators", *Phys. Today* 62, 44-49 (2009).

[8] J. A. Fülöp, *et al.,* "Efcient generation of THz pulses with 0.4 mJ energy", *Opt. Express* 22, 20155-20163 (2014).

[9] M. Shalaby and C. P. Hauri "Demonstration of a low-frequency three-dimensional terahertz bullet with extreme brightness", *Nat. Commun.* 6, 5976 (2015).

[10] C. Kealhofer, *et al.,* "All-optical control and metrology of electron pulses", *Science* 352, 429-433 (2016).