Terahertz-driven electron acceleration

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Abstract

The AXSIS group at CFEL is conducting an investigation into terahertz-driven linear electron acceleration. Early runs of the experiment have already shown large accelerating gradients compared to those achievable through conventional RF-based techniques. Analysis of these datasets has been performed and the full results will be published later.

Contents

1. Introduction

Terahertz-driven electron acceleration is a relatively new area of research with great potential. It is possible to produce keV or MeV electrons in the laboratory using this technique, without the need for kilometres-long accelerators. The accelerating gradients which can be achieved using THz-driven electron acceleration are potentially able to provide fields of up to 1 GVm^{-1}. While this is smaller than the gradients achievable using plasma wakefield acceleration, THz-driven acceleration produces stable electron beams which can be more easily controlled and used for photon science, and still represents over a tenfold improvement in gradient when compared to conventional RF-based accelerators. This report describes an experiment conducted over the summer of 2016, in the Centre for Free-Electron Laser Science (CFEL), at the DESY campus in Hamburg.

2. Theory

The term ‘Terahertz radiation’ refers to electromagnetic waves with frequencies in the range 0.3 to 3 THz, corresponding to wavelengths of around 0.1 to 1 millimetre. This places it between infrared and microwave radiation on the electromagnetic spectrum. Terahertz and infrared radiation can be used to accelerate electrons, a technique known as photonic linear acceleration.

Terahertz (THz) pulses can be produced by optical rectification. This nonlinear optical effect occurs in various media, including certain crystals, semiconductors and organic materials. For an optically nonlinear material to be used for optical rectification, it must exhibit $\chi^{(2)}$ nonlinearity; that is, its second-order electric susceptibility should be nonlinear. Light propagating through a transparent medium induces an electric polarisation in the medium [1], which also propagates through the medium. For materials with a $\chi^{(2)}$ nonlinearity, this nonlinear polarisation has a DC component [2]. This is the process known as optical rectification.

The electric field can be applied by a femtosecond-pulsed optical laser pump source, resulting in the emission of THz waves [3]. The energy of the emitted THz pulse is increased as the pump pulse duration is reduced, and pump pulse energy increased. However, it is challenging to produce high-energy THz pulses: in practice, the conversion efficiency from pump pulse energy to THz pulse energy is typically below 4%, with the theoretical maximum being 6% [4].

To maximise the acceleration of the electrons, the electromagnetic wave must be phase matched with the electron bunch. This is easier to achieve using THz radiation than infra-red, making THz an attractive choice for photonic linear accelerators. Using an appropriate waveguide and a polarised THz beam, efficient acceleration can be achieved.

The THz radiation, being electromagnetic, has both electric and magnetic field components, which oscillate in phase and orthogonal to each other. In this experiment, the laser pulses are polarised such that the electric component acts in the plane of motion of the electrons, and the laser is fired perpendicular to the direction of propagation of the electron bunch. As shown in Fig. 1, this means that electrons will be accelerated by the electric field. Due to the nonzero length of the electron bunch, the electrons are not uniformly accelerated.

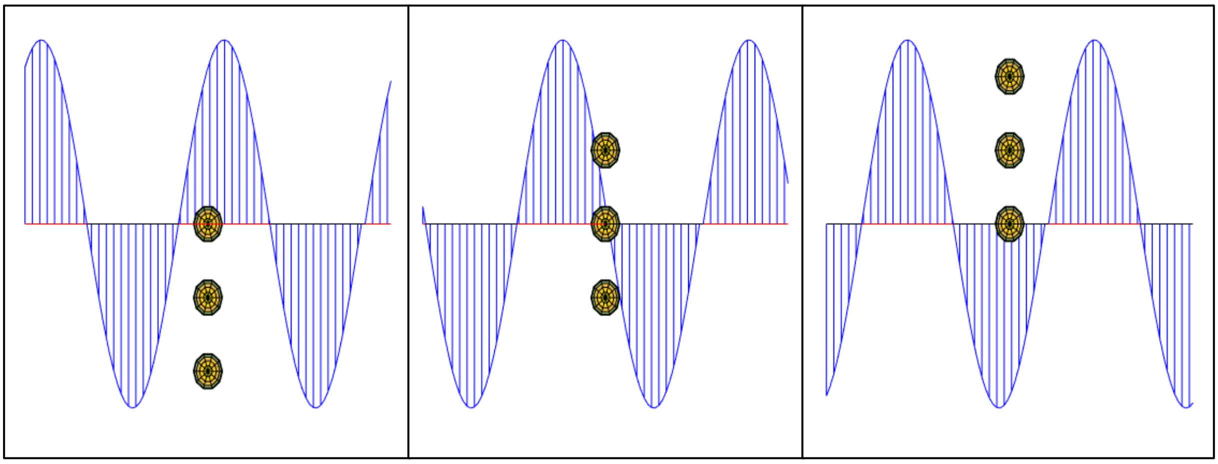

Figure 1: Sketch of electron interaction with THz, viewed from above. The electron bunch moves upwards while the electric field of the THz moves to the left. Each electron is hit by the field at a different phase, and feels a different acceleration.

Electrons in the bunch also interact with the magnetic component of the THz radiation. As charged particles, they feel a force with a magnitude given by:

$$F = qvB \sin\theta, \quad (1)$$

where q is the charge on the particle, v is its velocity, B is the magnitude of the magnetic field, and θ is the angle between the particle's direction and the magnetic field. This force acts perpendicular to their direction of motion: their paths become curved. It is possible to further curve the paths of electrons by placing a dipole magnet in their path. The higher energy electrons, having higher velocity, feel a larger force and their paths are therefore more curved. Knowing the electron deflection caused by the laser, the change in energy can be calculated.

Previous investigations into direct THz-driven electron acceleration have shown promising results. In 2015, an energy gain of 7 keV in a 3mm structure was observed [5], and it was predicted that a higher-energy THz pulse would result in even higher accelerating gradients. Terahertz-driven acceleration could therefore prove enormously useful: if MeV or GeV electrons can be produced in a normal-sized laboratory, the size and cost of future linear accelerators can be drastically reduced. Electrons produced by this method have applications in X-ray production, such as for medical imaging or materials science. In the future, THz-accelerated electrons could be used to build a free-electron sub-femtosecond-pulsed X-ray laser, which could be used to probe rapid chemical processes such as photosynthesis [6]. Currently, the limiting factor for this technique is the THz pulse energy, but in the near future it is expected to be possible to produce THz pulse energies on the 10mJ scale.

3. Methods

3.1. Experiment

The pump source energy is increased using chirped pulse amplification: the pulse is stretched out, amplified, and recompressed, allowing energies which would damage the optics were the pulse amplified by conventional means. The amplified pulses are sent through a cryogenically-cooled $LiNbO_3$ crystal, producing THz pulses by optical rectification. Due to nonlinear optical effects, cooling the crystal increases the pulse energy significantly. The THz pulses are focused into the vacuum chamber by a TPX THz lens.

Electrons are produced by the photoelectric effect: a UV laser incident upon a photocathode stimulates emission, and the electrons are accelerated by a large voltage before entering the THz accelerating structure. The structure is mounted on a motorised stage, allowing precise incremental movements.

After being hit by the THz beam, the electrons travel through the vacuum chamber and hit a micro channel plate (MCP), amplifying the signal produced. The MCP emits many more electrons, which hit a phosphor screen and induce photon emission. The photons are emitted from the other side of the screen, where they pass through a lens and are detected by a CCD, which saves images in the FITS format. FITS files contain the image array and an image header of metadata, including the time the image was taken, the type of instrument used, and the real-world size of each pixel. This metadata is useful in analysing the results. During initial runs of the experiment, a pair of images was taken for each stage position – one control image with the THz blocked by a shutter, and one image where the beam was allowed to interact with the electron bunch. In later runs, all images were taken with the beam unblocked.

3.2. Analysis

Analysis of the images was performed in MATLAB. Due to some significant noise, a median filter was applied (see Appendix 5.1). Some experimental runs were subject to UV beam leakage, obscuring the electron beam. The images were therefore cropped as necessary. Using MATLAB, the position and intensity of peaks in the image could be determined. Pixel intensity in the CCD images corresponds to the density of electrons hitting the phosphor screen, and can be used to identify the position and therefore acceleration of the electrons. For the runs which included control images, the peak shift induced by THz was measured and plotted. For the runs without control images, the peak position for each image was plotted. Knowing the experimental parameters, the image data was processed, allowing the change in electron energy for each stage position to be displayed.

In order to save time spent analysing the data, a GUI was developed in MATLAB. The interface is shown in Fig. 2 and will be used to analyse data from future runs of the experiment. This will enable users to quickly determine whether a run was successful, and visually identify which stage positions are most effective for electron acceleration.

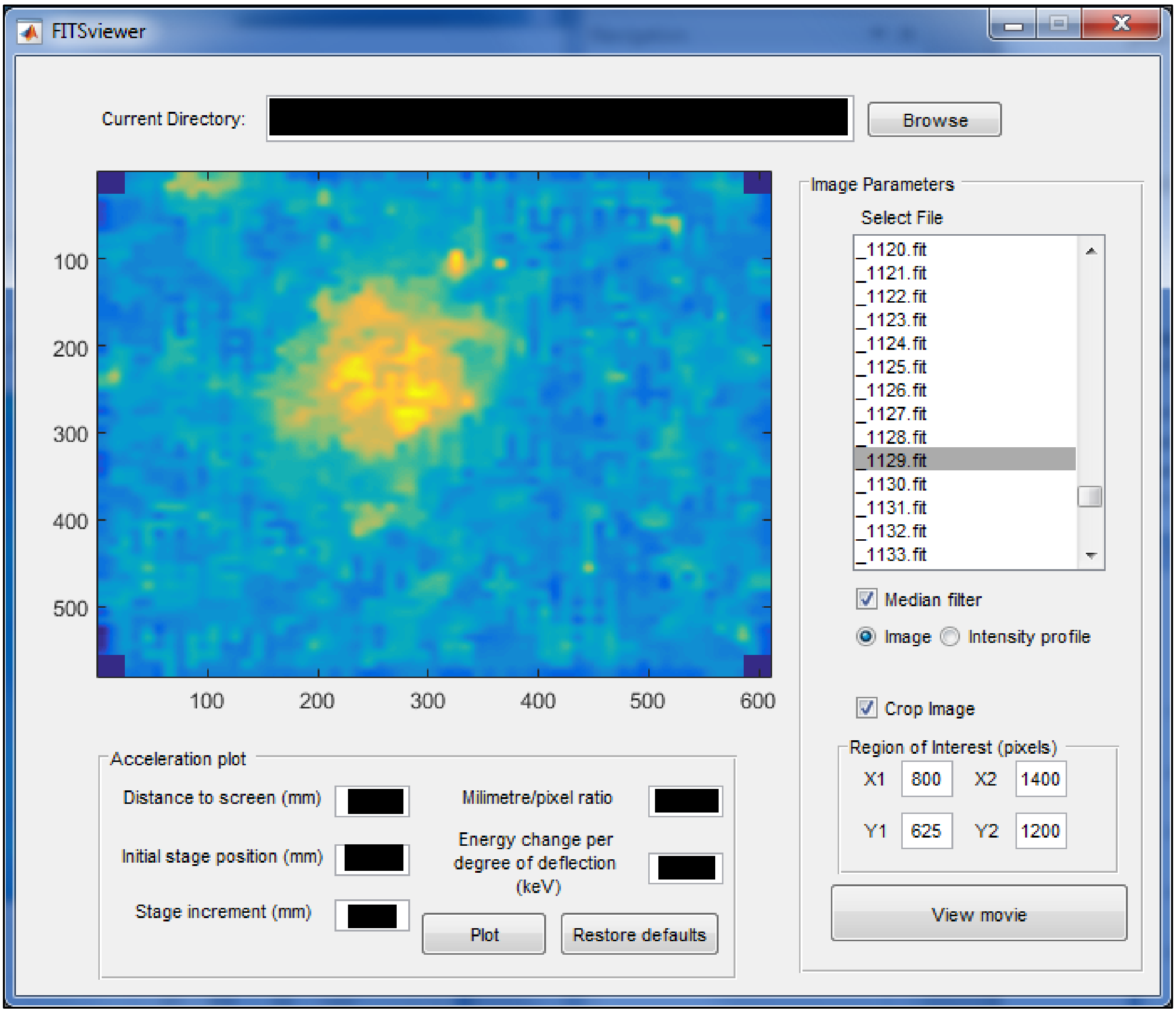

Figure 2: MATLAB GUI for processing FITS images. The user can select a directory and view any .fit or .fits image therein. It is possible to apply a median filter, view the intensity profile, and produce a movie comprised of every FITS image in the directory. If the user knows the parameters of the experiment, additional plots displaying the peak position for each stage position, or electron density for each stage position, can be viewed.

4. Results

At this time, it is not possible to publically present the results of the experiment, as the full results and analysis will be published by CFEL in the future.

5. References

1. R. Paschotta, article on 'nonlinear polarisation' in the *Encyclopedia of Laser Physics and Technology,* <https://www.rp-photonics.com/nonlinear_polarization.html>, accessed on 05-09-16
2. M. Bass et al. *Physical Review Letters*/Vol.9, No.11 (1962)
3. A. Schneider et al. *Journal of the Optical Society of America B*/Vol.23, No.9 (2006)
4. S. Huang et al. *Optics Letters*/Vol.38, No.5 (2013)
5. E. Nanni et al. *Nature Communications 6* (2015)
6. *Max Planck Institute,* < http://www.mpsd.mpg.de/196865/2015-10-THz-accelerators-miller>, accessed on 05-09-16

6. Appendix

6.1. FITS filtering

As discussed in the Analysis section, median filtering was used to make the FITS images clearer. To illustrate this, an image from the experiment is shown in Fig. 3, with and without filtering. Intensity profiles are also displayed.

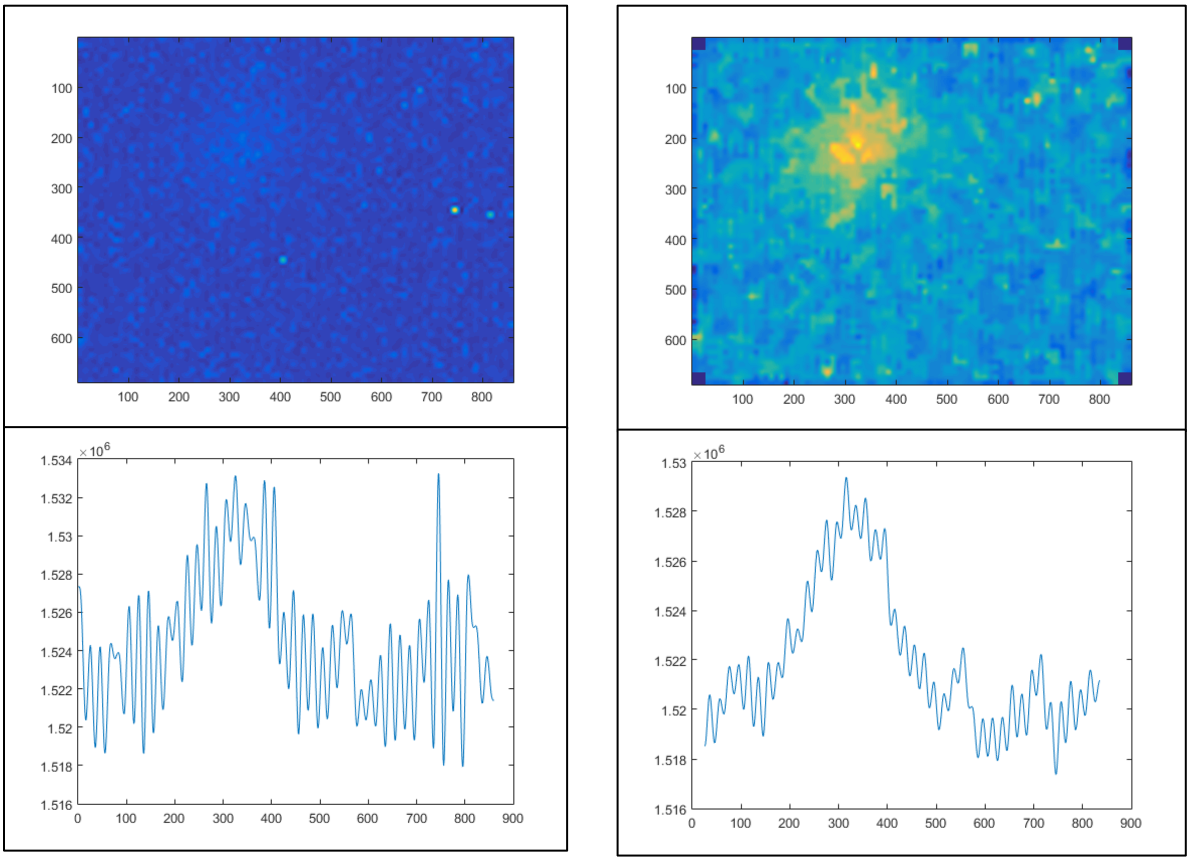

Figure 3: FITS images shown before and after application of a median filter. Beneath each image is the corresponding intensity profile. The median filter examines a 3 by 3 grid around each pixel and assigns it the median value of the pixels in the grid. The extreme-valued pixel on the right-hand side of the unfiltered image obscures the true data. In addition, it is difficult to identify the position of the beam from the intensity profile unless a filter is applied.

6.2. Additional MATLAB interfaces

Over the course of the experiment, two additional GUIs were developed to automate the monitoring of experimental parameters. They are described here.

Temperature GUI

During initial runs of the experiment, the THz beam was generated through a nitrogen-cooled $LiNbO_3$ crystal to increase the pulse energy. The cooling is achieved by mounting the crystal in a chamber below a tank of liquid nitrogen. In order to reach the ideal temperatures of around 100K, the tank must be replenished with nitrogen several times. Therefore, it is useful to graphically display the temperature trend of the crystal, so that it is obvious when the temperature begins to rise again. In addition, it may be useful to know the rate of temperature change in the crystal – if cooled too quickly, the crystal could be irreparably damaged.

A temperature sensor is mounted adjacent to the crystal, and connected to a LakeShore 211 Temperature Monitor. This can be connected to a computer using an RS-232 serial port, and can send and receive ASCII strings to and from a MATLAB interface. Temperature data is recorded at user-defined intervals, stored in an array, and plotted on the GUI, as shown in Figure 3.

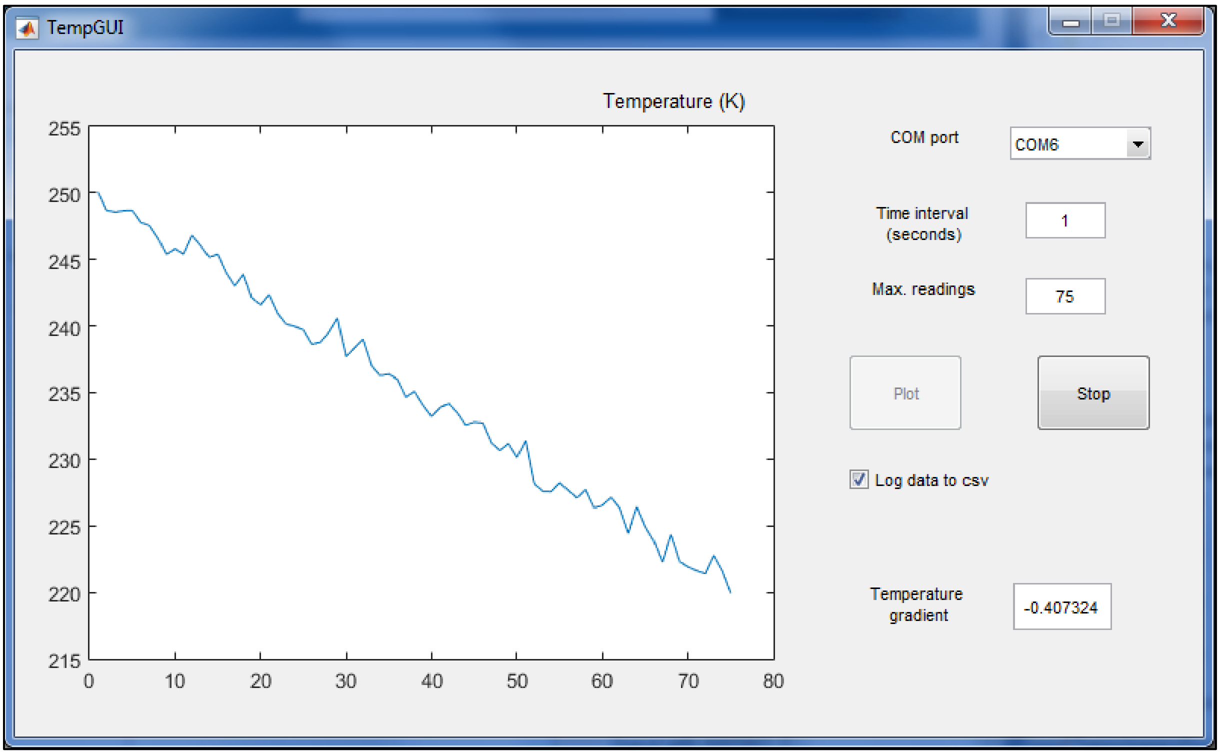

Figure 4: MATLAB GUI for monitoring the crystal temperature. The user can select a COM port to connect to, enter a time interval and array size for temperature measurement, and optionally log the data to a csv file.

Vacuum Monitor

The vacuum chamber is pumped to very low vacuum using two different vacuum pumps. The vacuum level is monitored by a Pfeiffer TPG 361 SingleGauge Controller. It is desirable to automate the monitoring of the vacuum level, as pumping the chamber takes some time, and a pump malfunction could result in damage to the apparatus. To this end, a similar GUI was developed to visualise the trend of the vacuum level. The Pfeiffer TPG 361, unlike the LakeShore 211, communicates using decimal representations of Unicode characters using an RS-485 interface, but in other respects the code used is analogous to that developed for the temperature GUI.