Final report on NKFI project 129134, entitled

Carrier-envelope phase stable few-cycle pulse generation by undulator radiation

1. Introduction

Over the past sixty years, there has been continuous advancement in the development of light sources based on electron accelerators applying synchrotron radiation. The brightness of the produced radiation has grown exponentially during this time. In the last two decades, groundbreaking advancements have been made by developing fourth-generation light sources such as X-ray free electron lasers. These light sources offer unprecedented scientific research opportunities, as they can generate radiation from the ultraviolet to angstrom wavelengths. The energy of these pulses is the largest in the world in the EUV – X-ray wavelength range, and their values exceed the mJ-level. However, the waveform of the pulses is stochastic.

Our proposed setup allows the generation of carrier-envelope phase stable attosecond pulses in the extreme ultraviolet range. The setup is based on a relativistic electron beam generated in a linear accelerator. After acceleration, it is sent through a modulator undulator, where an intense laser pulse is superimposed on it to modulate the electron beam's phase space. The electron beam then propagates through a chicane, and its energy modulation leads to the formation of a train of electron layers, i.e., microbunches. Finally, the ultrashort electron beam passes through a single- or few-period radiator undulator, wherein undulator radiation is generated. The waveform resembles the longitudinal distribution of the magnetic field of the radiator undulator. Efficient radiation can be generated if the microbunch length is shorter than half of the wavelength.

Rescaling of the carrier-envelope phase controlled attosecond pulse generation setup is possible by adjusting the energy of the electrons utilized in the system. For instance, the system could be tested on a particle accelerator with an energy range below 30 MeV. The electron beam manipulation could be achieved using a terahertz (THz) pulse, and the generated pulse would also be in the THz range. To carry out this implementation, a group of international partners joined forces. Regrettably, the proposal by the consortium was turned down. Therefore the originally planned proof-of-principle experiment could not be prepared. However, I continued working on problems similar to the original plan. The originally planned task consists of four main parts: (1) electron gun and linear accelerator investigation, (2) THz pulse generation, (3) electron beam manipulation by THz pulses, and (4) undulator radiation.

This report summarizes the results of these research topics.

2. Research results

2.1. Electron gun and linear accelerator investigation

With the leadership of Uppsala University colleagues, in our study [Shamuilov-2022], we have discovered an unusual regime of emittance self-compensation in an electron bunch produced by a radio-frequency photocathode gun in blow-out mode. This regime occurs while the strong space-charge field on the cathode reaches approximately 30-35% of the accelerating field. The simulations indicate that the projected emittance initially increases, but later it becomes self-compensated due to the combined effects of strong space-charge forces of mirror charged, an energy chirp in the bunch, and substantial reshaping of the electron bunch. We have demonstrated through analytical and numerical methods that a complex interplay among these effects results in emittance self-compensation at the gun exit. This discovered self-compensation has been observed over a broad range of bunch charges from 160 fC to 16 pC and for various lengths of the accelerating gun. Generally, the emittance self-compensation mechanism is robust if the initial radial distribution of the bunch density must be half-circular to maintain linear space-charge forces. The effect of self-compensation in blow-out mode with strong space-charge forces appears to be universal. However, the specific settings of the gun determine the extent and position of self-compensation. High-brightness electron beams are critical for applications such as ultrafast electron diffraction experiments and accelerator-based light sources. This newly discovered mode of operation is expected to provide a new level of performance for these machines.

Electron acceleration using THz pulses in waveguide structures has numerous benefits over traditional particle accelerators, including compactness, scalability, and cost-effectiveness. These benefits make the proposed technique a promising alternative to conventional accelerators. Our publication presents a new method utilizing THz pulses to create a high electric field within a waveguide structure to accelerate electrons [Turnar-2022]. The waveguide structure consists of two parallel metallic plates that guide the THz pulses and increase the waveguide channel's peak electric field. Figure 1a-c shows the view of the waveguide and the setup. The electrons are generated in the waveguide, where they experience the electric field of the THz pulses. Due to the optimized electron-electric field interaction, an effective particle acceleration could be achieved. Numerical simulations were conducted to study the acceleration mechanism and optimize the waveguide structure. To measure the THz pulse waveform, reflective electro-optic sampling (EOS) was used at the exit plane of the opened horn gun. The experimental and simulation results agreed with each other, considering both the field enhancement and the development of the THz pulse shape inside the horn. Theoretical calculations showed the acceleration of a femtocoulomb (1 fC) electron bunch from rest to a mean energy of 8 keV, with a root-mean-square (rms) energy spread of 6.7%. Figure 1d shows the energy evolution of the electron bunch along the propagation direction. The calculations suggest that the waveguide structure can produce a sufficient acceleration gradient for femtocoulomb electron bunches.

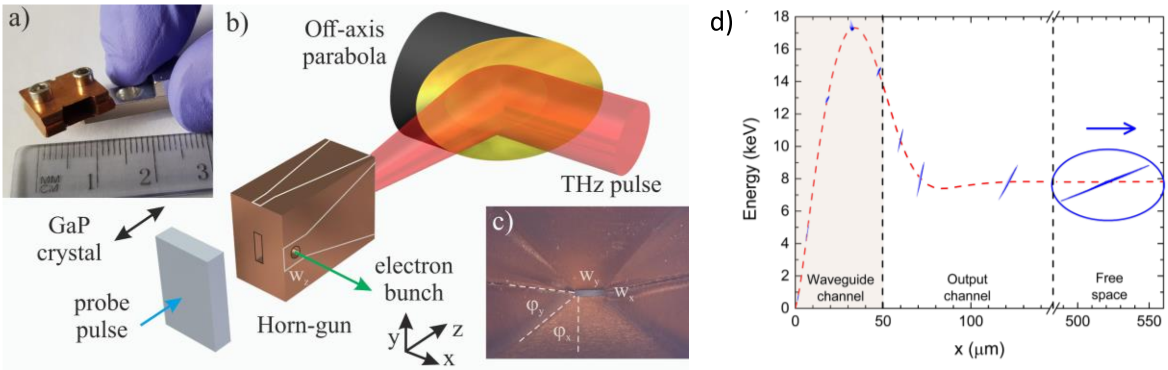

Figure 1: (a) Horn gun-based electron gun. (b) Schematic view of the experiment. (c) Inside view of the horn-gun (d) Energy evolution of the electron bunch along the propagation direction. The phase-space distribution of the electron bunch is indicated at a few positions by blue color [Turnar-2022]

2.2. THz pulse generation

Intense THz pulses are necessary for manipulating charged particles. In the case of electron manipulation, a peak electric field of >100 kV/cm is required. As a result, numerous THz pulse generation setups have been proposed recently to achieve the highest possible electric field.

Our article proposes and examines efficient and scalable sources of THz pulses based on optical rectification in microstructured semiconductors, specifically in GaP [Tibai-2022a]. Two setups were considered: GaP reflective nonlinear slab with external structured reflector (GaP RNLS-ESR) and GaP-nonlinear echelon slab (NLES), which introduces pulse-front tilt using a periodic structure on the back surface of the nonlinear material or a volume phase holographic grating, respectively. The schematic view of the setups is shown in Figure 2. Both setups have higher pump-to-THz conversion and diffraction efficiency than the contact grating (CG) setup. Furthermore, using amorphous selenium between the external structured reflector and the GaP material-RNLS-ESR setup makes implementation easier than using nanocomposite liquids as a refractive index matching medium. Simulation results show that almost single-cycle THz pulses can be generated in a 4 mm thick crystal with 0.4% conversion efficiency in the GaP-NLES BK7 refractive index matching liquid-filled setup without assuming antireflection coating for the generated THz pulses. Assuming a pump energy of 20 mJ in the GaP-NLES BK7 refractive index matching liquid-filled setup, an expected focused peak THz electric field of around 17 MV/cm can be achieved, which is applicable for particle manipulation.

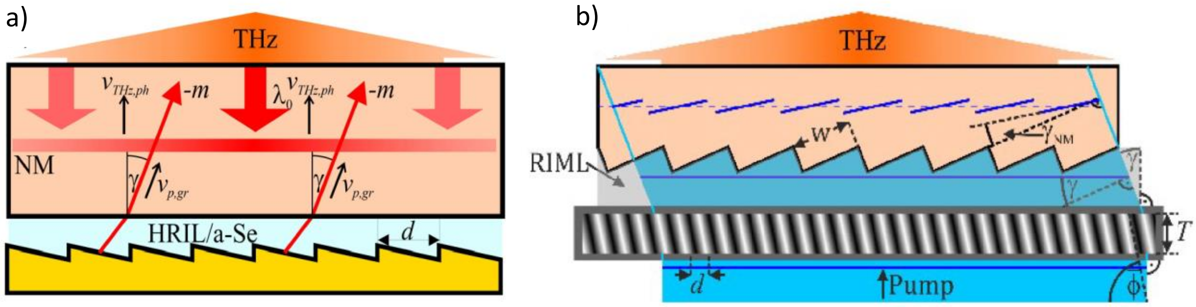

Figure 2. (a) GaP-RNLS-ESR THz source. (b) HRIL is used between the NM and the ESR for optical coupling GaP-NLES THz sources RIML-filled configuration [Tibai-2022a]

We used numerical calculations to investigate different ways to increase the diffraction efficiency in the semiconductor contact-grating THz sources for further upscaling of THz pulse energy and field strength along the infrared pump wavelength range [Tibai-2022b]. Three types of antireflection coating (ARC) structures were considered to decrease the pump's Fresnel reflection and increase the diffraction efficiency of the +/-1st-order beams, which are responsible for the THz pulse generation. The parameters of the CG belonging to the highest diffraction efficiency differ in the cases of having and not having ARC. Based on rectangular contact-grating profiles, by adding an appropriate antireflection coating on the gratings, diffraction efficiencies greater than 91% and 89% can be realized in gallium phosphide and gallium arsenide, respectively.

We proposed a novel THz pulse source that is imaging-free, plane-parallel, and easy to manufacture [Krizsán-2020]. This setup is particularly advantageous for nonlinear materials with a phase-matching angle greater than 60 degrees. It is an improved version of the reflection nonlinear slab setup and enables upscaling THz pulse energy without significant limitations. We used a periodically micro-structured external metal profile to introduce the necessary phase-matching angle for velocity matching. We used a high refractive index liquid for optical coupling between the nonlinear material and the metal surface. We provided examples of making nanocomposite fluids with the appropriate refractive index for high refractive index liquid. We conducted numerical simulations to predict the diffraction efficiencies achievable for lithium niobate (LN) and lithium tantalate (LT) nonlinear materials for 800 nm and 1030 nm wavelengths. We expect THz generation with significantly larger than 1 % efficiency with cryogenic cooling.

A novel THz source, based on optical rectification in $LiNbO_3$ using the tilted-pulse-front technique, was proposed in 2022 [Krizsán-2022]. The pulse-front tilt was introduced by a volume phase holographic grating (VPHG). Such gratings can be used efficiently at perpendicular incidence in transmission, in contrast to the conventional Littrow configuration. THz pulses were produced in a $LiNbO_3$ plane-parallel nonlinear echelon slab. The compact and imaging-free setup has a plane-parallel transmission-type geometry, which enables distortion-free scaling to large sizes, high pulse energies, and THz field strengths.

We analyzed the limitations of recently proposed high-energy LN sources. We found that the nonlinear echelon slab with and without imaging and reflection nonlinear slab pumping schemes can reduce the limitations of the conventional tilted-pulse-front-pumping LN THz source [Tóth2021]. A comparison of different setups showed that the new setups could significantly enhance the available THz pulse energy and beam quality compared to the conventional setup. The reflective nonlinear slab setup enables new applications requiring multi-mJ THz pulses, such as particle acceleration and manipulation, generation of attosecond pulses, orientation, and alignment of molecules. These applications could benefit from the availability of THz sources producing focused field strength in the few 10 MV/cm regime.

2.3. Electron beam manipulation by THz pulses

In 2021 we numerically investigated the electron acceleration and manipulation driven by THz pulses [Turnár-2021]. The proposed setup is based on counter-propagating single-cycle THz pulses, which create a transient standing wave. The waveform and the polarization direction of the THz pulses are the same. In this case, the magnetic fields of the two THz pulses have opposite directions, thereby minimizing magnetic deflection effects on the electrons. Our proposed setup can work in an electron gun and bunch compressor mode. The superposed electric field of the THz pulses was used to accelerate the electrons. On the other mode, the polarity of the THz pulse is reversed to reduce the longitudinal size of the bunch. The simulations predict the production of electron bunches with 20 fC charge, 80 keV energy, and 1.0 % relative energy spread. According to the simulations, the electron beam can be compressed by THz pulses below 100 fs. Furthermore, electron bunch with 346 keV energy and as short as 200 fs duration can be generated using a post-acceleration and bunch compressor stage. The phase-space distribution of the bunch before and after the compression is shown in Figure 3.

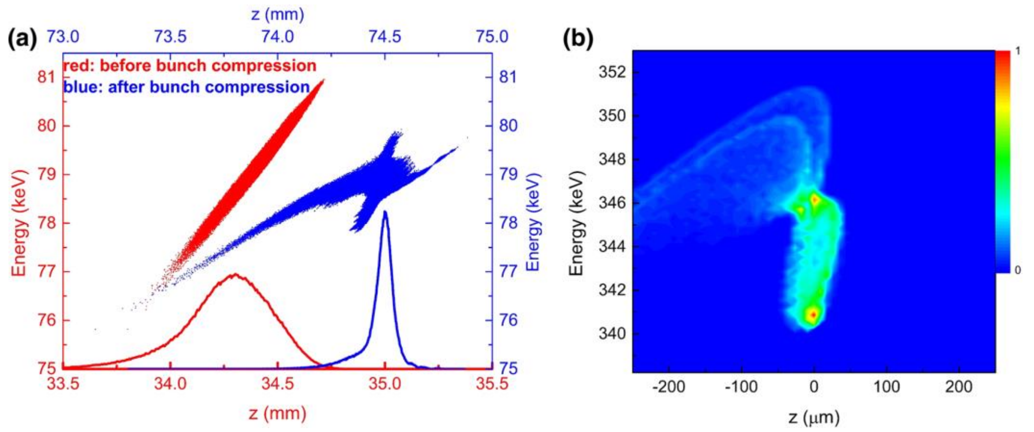

Figure 3. (a) Phase-space distribution of the bunch before (red) and after (blue) the longitudinal bunch compression. (b) Phase-space distribution of the compressed bunch.

An improved model for electron acceleration in a vacuum using high-energy THz pulses is presented in [Tibai-2022c]. The model incorporates spatiotemporal effects and includes the examination of the acceleration using 300 GHz and 3.0 THz central frequency THz pulses with properties typical of common sources. The calculations compared Gaussian and Poisson amplitude spectra and associated time profiles of the electric fields. The model accounts for both the longitudinal field and the spatio-spectral evolution around the focus, which are necessary due to the tight focusing and the short duration towards a single-cycle of the THz pulses, respectively. To optimize the acceleration scheme, the carrier-to-envelope phase (CEP) and the tilting angle of the coincident few- or single-cycle THz pulses must be adjusted in all cases. Moreover, the study suggests that electron beams with different final energies and divergences can be generated based on simulated THz pulses having different Porras factors, which describe the frequency dependence of the spatiotemporal amplitude profile. The Porras factors may depend significantly on the method used to generate the single-cycle THz pulses.

2.4. Generation of carrier-envelope phase undulator radiation generation

Using the FLASH accelerator, we proposed a robust method for producing CEP-controlled few-cycle attosecond pulses in the XUV spectral range [Tibai-2018]. The schematic view of the proposed setup is shown in Figure 4. The method uses an established linear accelerator and laser technology in a novel parameter range. Extremely short nanobunches can be generated in a double-period modulator undulator using a multi-TW short-wavelength laser (800 nm). By placing a radiator undulator in the temporal focus, intense XUV pulses can be generated with a controlled waveform conveniently defined by the on-axis radiator undulator magnetic field structure. Our calculations predict single-cycle CEP-stable pulses with 14 nJ energy at 10 nm wavelength with 35 attosecond pulse duration. Scaling the energy of the attosecond pulse with varying the radiation wavelength and the radiator undulator parameter were investigated. According to the numerical simulations, the nanobunches emit 20 attosecond pulses at 5 nm wavelength with 10 nJ energy, 80 attosecond pulses at 20 nm wavelength with 90 nJ energy, and 240-as pulses at 60 nm wavelength with 200 nJ energy for K=0.5 undulator parameter.

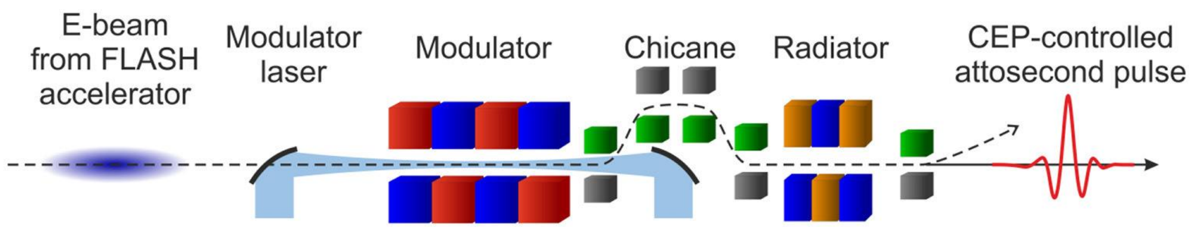

Figure 4. Scheme of the investigated setup.

During the project, with the leadership of Vitaliy Goryaskho, we published a review article entitled "Matter manipulation with extreme terahertz light: Progress in the enabling THz technology" ([Salén-2019]). This publication includes the main THz generation techniques and their applications, such as THz manipulation of electron beams.

3. Summary of the research and publication results

In summary, we have achieved significant results in both the attosecond pulse generation, the THz pulse generation, and THz pulse-based electron manipulation. Regrettably, the consortium's proposal (which had members from Uppsala University, DESY PITZ, Strathclyde University, etc.) was rejected. Therefore we could not prepare an experimental demonstration of single-cycle undulator radiation. Nevertheless, due to this project, I could spend 1-1 month at Uppsala University (regrettably, the second trip was interrupted because of the COVID pandemic and the border close), where I learned a lot. Moreover, thanks to the time spent there, we achieved significant results in recent years, which we also published in an international journal. The collaboration with them is still active today. Last but not least, we could purchase an electron gun thanks to this project, which will decisively promote current and future research. I have to note that the onset of the COVID pandemic in the middle of the originally planned project created difficult conditions.

Considering these not-exactly favorable circumstances, the project was very successful. In contrast to the originally predicted 3 papers, we have published our results in 11 refereed journal papers.

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