UNIVERSITY OF PÉCS

Physics Doctoral School

Nonlinear Optics and Spectroscopy Programme

Relativistic electronbunch generation on nanometer scale based on laser-driven energy modulation

PhD Thesis

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1. PRELIMINARIES AND OBJECTS

High-energy electrons generated by linear accelerators are applicable for synchrotron and free electron laser (FEL) sources. These light sources have a significant role in several disciplines, including biology [1], chemistry [2], and physics.

Due to technological progress not only relativistic electrons but also light source parameters based on these electrons have evolved too. This advancement is contributed to the swift development of laser physics, whereas lasers can be applied to electron manipulation. Laser based manipulation enables changing electrons distribution in the phase-space. These amendments are advantageous for a couple of applications. For example improvement of longitudinal coherence and pulse shortening during generation of radiation in an undulator, or increasing efficiency while accelerating electrons with inverse FELs.

Implementation of laser based electron modulation is possible through a set of periodically placed, static magnets (modulator undulator) and a laser field. In furtherance of changing in electron longitudinal distribution – bunching of electron – a special (dispersive magnet) is needed. Energy of relativistic electron bunch depends on the laser phase while propagating through the modulator undulator. Subsequently followed by the dispersive magnet which diverts electrons in different energy level to different routes. After stepping out from the chicane a so called bunching takes place. In case of high energy modulation, bunching can occur even after a few meters from the undulator in free space. So application of a chicane is neglectable. This gives the benefit of increased intensity and coherence of the generated radiation.

There are several electron manipulation techniques, that are differentiated by the combination of the three main components. For example seeded FEL with two sub-types High Gain Harmonic Generation (HGHG) and Echo Enabled Harmonic Generation (EEHG). One of the main application area of these methods is femtosecond pulse generation in the extreme ultraviolet [3] and in the x-ray range [4]. First experimental results were achieved in the infrared [5] and in the ultraviolet [6] range. Nowadays, through HGHG experiments pulses with 133 nm [7] and 60 nm central wavelength are realized by laser pulses as modulator laser generated by high harmonic generation in gases. Several proposals were made based on theoretical calculations, on even shorter, attosecond pulses generated by electron manipulation [8], achieving the μJ range [9]. Disadvantage from practical perspective of these methods are the stochastic behavior of the temporal shape and carrier-envelope phase.

We proposed a solution on that issue in 2014. According to our numerical calculations with our layout it is possible to generate carrier-envelope phase stable single-cycle attosecond pulses in the extreme-ultraviolet range [10]. Our method is based on electrons accelerated in a linear accelerator (LINAC). The electrons propagate through a modulator undulator and interact with a terawatt laser field, where ultrathin electron layers, nanobunches are produced. Afterwards the nanobunched electrons pass through a (radiator) undulator. Radiation is generated as the bunch propagates with a transversal velocity component. Temporal shape of the radiation resembles the radiator undulator's spatial magnetic field distribution. The model consist of two parts. Firstly, ultrathin electron layer production that can be done by laser based electron manipulation. Secondly, a coherent undulator radiation. In this dissertation I deal with the generation and generation optimization through numerical simulations of ultrathin electron layers.

In the scientific achievements part of my dissertation I propose a method to produce shorter than 10 nm, ultrathin electron bunches. Part in the model involve a modulator undulator, a high power laser, and relativistic electron bunches. As practical consideration I specify a parameter set to generate the nanobunches mentioned as objective. Furthermore, all parts in my numerical calculations are realistic. The parts I apply to the scheme are studied in detail. Afterward optimized so, that the produced electron bunch is as short as possible.

2. METHODS

Simulation models and software solutions for FEL have improved greatly throughout the past years. Rapid increase in computing power had a great role in this process, whereas simulation of few million particles became available.

Calculations involving electron manipulation were carried out by Genesis [11] and General Particle Tracer (GPT) [12]. Vast majority of numerical studies in this thesis were done in GPT. With the help of GPT – written in C++ – I simulated the interaction among undulator, high intensity laser field, and relativistic electron bunch.

I developed a code on C# to optimize energy modulation generated by the interaction of these three elements. The code describes the propagation of one single electron through an undulator with arbitrary period, strength, and trim. The simulation also involves the electromagnetic field of a Gaussian-beam focused into the middle of the undulator. Time needed to optimize the ideal undulator period and undulator length is shorter with my own code than with GPT. Thus, it is used to pre-optimize the setup and calculate the parameters where the energy gain inside the undulator is maximum.

3. NEW SCIENTIFIC ACHIEVEMENTS

I. I showed with model calculations that in the magnetic field of an undulator a high power (> 1 TW) modulator laser introduces a periodic energy modulation in the electrons. The evolving electron bunches can be shorter than 10 nm along the longitudinal axis. During the investigation of the effect of a 516-nm central wavelength laser power variation on electron bunch longitudinal lengths I showed that one can produce 9 nm short electron bunch by a 4 TW power laser pulse, and 6 nm electron bunches by a 10 TW power laser pulse. [S1-S5]

II. I showed for a double-period modulator undulator and a tightly focused modulator laser configuration, that maximum energy modulation ($\Delta\gamma$) is not determined by the resonance conditions paramteres undulator period (λ_u), the effect is related to Gouy-phase. To achieve maximum energy modulation a 20% longer undulator period is needed. This maxima is 10% larger than the one calculated with the parameters stratifying the resonance condition. [S1,S5]

III. I showed that the recently proposed formation method of nanobunches, that produce few-cycle attosecond pulses, is feasible if the e-beam has a relative energy spread be below 0.2%. In accordance with the literature I showed the dependence of the nanobunch length on energy spread is linear above 0.1% energy spread. I concluded that the dependence of the nanobunch length on energy spread becomes nonlinear below 0.1% energy spread, the effect is related to

Coulomb interaction. As my results show generated nanobunch length has a minimum value of 5 nm. [S1]

IV. Laser power has a great influence on the electronbunch length and position of generation. As practical consideration I determined the deviation from the optimum 6 nm on the effect of modulator laser instability at the position of the 6 nm electronbunch - described in thesis point I. Calculations for ±10% and ±5% intensity variation show that electron bunch lengths are 35% and 20%, respectively. According to my results great care should be taken to laser power fluctuations.[S1]

V. I investigated the full-charge dependence in electron bunches generated during energy modulation modulator lasers for different wavelengths. I confirmed with calculations that full-charge in electronbunches increases linearly with laser wavelength at the range of 516 – 1064-nm scale. I chose the modulator laser wavelengths 516 nm, 800 nm, and 1064 nm, and the generated electronbunch charges are 1.1 pC, 1.8 pC és 2.1 pC, respectively. [S1, S4]

VI. I determined the longitudinal length ratio of main attosecond pulse to neighboring pulse generated throughout the bunching for pulsed modulator laser. My calculations show a ratio of 1:3 for 3 cycles of modulation pulses, and 1:4 for 2.5 cycles. Furthermore, for 2 cycles or less (<3.4 fs) the ratio decreases below 1:5, namely isolated attosecond pulses are generated.

VII. My investigations show that the proposed method is capable to generate ultrathin layers of electrons from laser-plasma based electron sources. Simulation show that electron bunch energy-spread can be decreased from

1% to 0.2% while applying a chicane, to ensure effective operation of the proposed arrangement. Obtainable charge from a laser-plasma based accelerator is not comparable to LINAC. Also, achievable electron nanobunches are longer than 10 nm. Thus, the generated energy is considerably lower, than the one obtained by LINAC source. Furthermore, carrier-envelope phase controlled attosecond pulses are generated only with 40 nm or longer central wavelengths. According to our calculations only 5 nJ attosecond pulses are produced with 60 nm central wavelength. This is 2% of the energy obtained by LINAC sources.

4. ARTICLES RELATED TO THE TOPIC OF THIS THESIS

[S1] **Z. Tibai**, Gy. Tóth, M. I. Mechler, J. A. Fülöp, G. Almási and J. Hebling, "Proposal for Carrier-Envelope-Phase Stable Single-Cycle Attosecond Pulse Generation in the Extreme-Ultraviolet Range", Phys. Rev. Lett. **113**, 104801 (2014).

[S2] Gy. Tóth, **Z. Tibai**, Zs. Nagy-Csiha, Zs. Márton, G. Almási and J. Hebling, "Circularly polarized carrier-envelope-phase stable attosecond pulse generation based on coherent undulator radiation", Opt. Lett. **40**(18), 4317-4320 (2015).

[S3] Gy. Tóth, **Z. Tibai**, Zs. Nagy-Csiha, Zs. Márton, G. Almási, J. Hebling, „Investigation of novel shape-controlled linearly and circularly polarized attosecond pulse sources”, Nuclear Instruments And Methods In Physics Research Section B-Beam Interactions With Materials and Atoms, **369**, 2-8 (2016).

[S4**] Z. Tibai**, Gy. Tóth, Zs. Nagy-Csiha, J. A. Fülöp, G. Almási, J. Hebling, „Carrier-Envelope-Phase Stable Linearly and Circularly Polarized Attosecond Pulse Sources”, in Proceedings of the 37th International Free-Electron Laser Conference, FEL2015, Daejeon, South-Korea, 2015, Report No. MOP071, (2015).

[S5] Szabadalmi bejelentés, Gábor Almási, Mátyás Mechler, György Tóth, **Zoltán Tibai**, János Hebling, „Method and Arrangement to Generate Few Optical

Cycle Coherent Electromagnetic Radiation in The EUV-VUV Domain", US 20160020574 A1.

5. OTHER ARTICLES

[S6] A. Sharma, **Z. Tibai**, J. Hebling, S. K. Mishra „Spatiotemporal focusing dynamics in plasmas at X-ray wavelength", Physics of Plasmas **21**, 033103 (2014).

6. REFERENCES

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