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Overview of Undulator Concepts for Attosecond Single-Cycle Light

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Abstract. The production of intense attosecond light pulses is an active area in accelerator research, motivated by the stringent demands of attosecond science: (i) short pulse duration for resolving the fast dynamics of electrons in atoms and molecules; (ii) high photon flux for probing and controlling such dynamics with high precision. While the free-electron laser (FEL) can deliver the highest brilliance amongst laboratory x-ray sources today, the pulse duration is typically 10–100 femtoseconds. A major obstacle to attaining attosecond duration is that the number of optical cycles increases with every undulator period. Hence, an FEL pulse typically contains tens or hundreds of cycles. In recent years, several novel concepts have been proposed to shift this paradigm, providing the basis for single-cycle pulses and paving the way towards high-brilliance attosecond light sources. This article gives an overview of these concepts.

1. Introduction

Thanks to the novel undulator concepts [1–8] proposed in recent years, accelerator-based light sources offer a means to generating intense *single-cycle* light pulses with a duration in the *attosecond* ($1 \text{ as} = 10^{-18}$ s) regime. These light sources could provide a pulse duration and a pulse energy beyond the reach of existing technologies, thus opening the doors to the unchartered territories in *attosecond science* [9, 10].

The novel concepts exploit the free-electron laser (FEL) principle [11], particularly the coherent radiation of relativistic electrons in undulators. Moreover, they feature the tailoring of the radiated wavefronts.

For the furtherance of this emerging research area, the LUSIA collaboration has been formed by the pioneers of the area. The collaboration currently comprises 9 research groups from 6 countries: Sweden, Germany, Hungary, Japan, Ukraine, United Kingdom. The acronym LUSIA stands for **A**ttosecond **SI**ngle-cycle **U**ndulator **L**ight.

The purpose of this article is to provide a brief overview of the subject. A thorough and elaborated review article will be published at a later time.

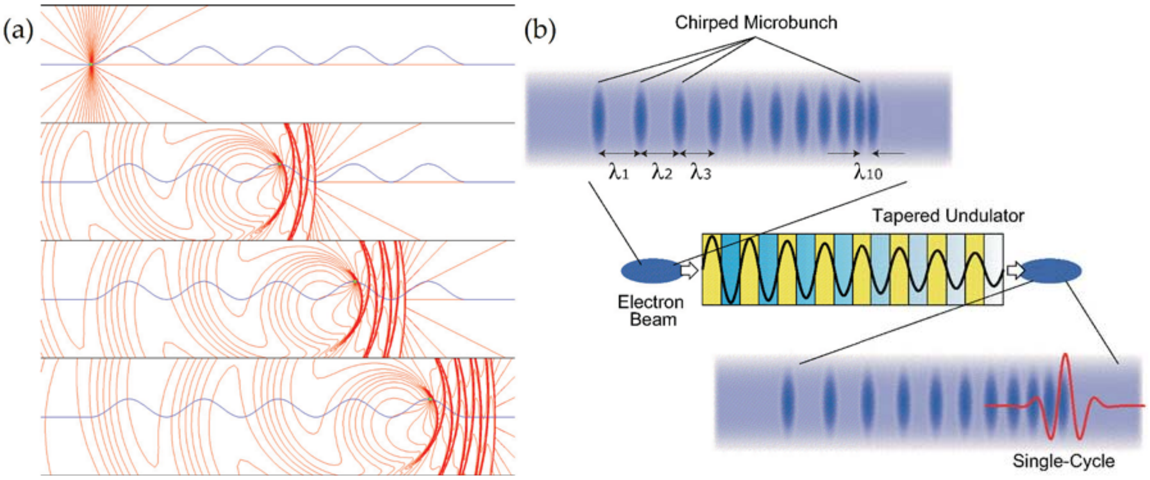

Figure 1. (a) Evolution of the field emitted by a microbunch along a planar undulator. The snapshots are made from the simulation tool of T. Shintake [20], with the blue curve being the microbunch trajectory and the red curves being the electric field lines. (b) The combined use of chirped microbunching and undulator taper yields an intense single-cycle light pulse.

1.1. Significance to Ultrafast Science

The access to *ultrashort* and *intense* light pulses is essential for the advancement of ultrafast science. In time-resolved microscopy and spectroscopy, for instance, a shorter pulse duration corresponds to a higher temporal resolution, and a higher pulse energy leads to a higher signal-to-noise ratio. At any given wavelength, the pulse duration can be significantly shortened by reducing the number of optical cycles within the pulse to *one*. For this reason, *single-cycle* light pulses are of great interest to ultrafast science.

In the x-ray spectral region, a single-cycle pulse has a duration at the *attosecond* scale. This provides the necessary temporal resolution to observe the rapid dynamics of electrons in atoms and molecules in real time [9, 10], thus making it possible to image [12] and control [13] the behaviour of electron wave packets within atoms.

High harmonic generation (HHG) in gas targets [14] is an established method of generating attosecond x-ray pulses, and a record pulse duration of 43 attoseconds is attained in 2017 [15]. However, HHG faces immense challenges in retaining a high photon flux when the pulse duration is reduced to the attosecond scale [16]. This limitation calls for a breakthrough in technology.

The FEL principle offers a promising new direction, as existing x-ray FELs have already delivered a billion-fold improvement [11] in brilliance over previous x-ray sources. Furthermore, FEL concepts provide a means to achieving a stable carrier-envelope phase (CEP) [3, 5]. This is crucial for CEP-sensitive strong-field phenomena [17, 18], as random CEP fluctuations from shot to shot can hinder the reproducible guiding of atomic processes [19].

1.2. Significance to Accelerator Physics

The FEL process relies on *microbunching*, whereby the electrons organize themselves into thin slices perpendicular to the propagation direction. Each slice, called a *microbunch*, is much thinner than the radiation wavelength λ.

In the standard FEL process, the microbunches are equally spaced at a distance of λ. They radiate coherently as they travel along the undulator, and the constructive interference of the emitted waves leads to an exponential growth in radiation intensity.

Along the undulator, the emitted waves travel faster than the electrons, and slip ahead of the electrons by a distance of λ for every undulator period. While the microbunches continue

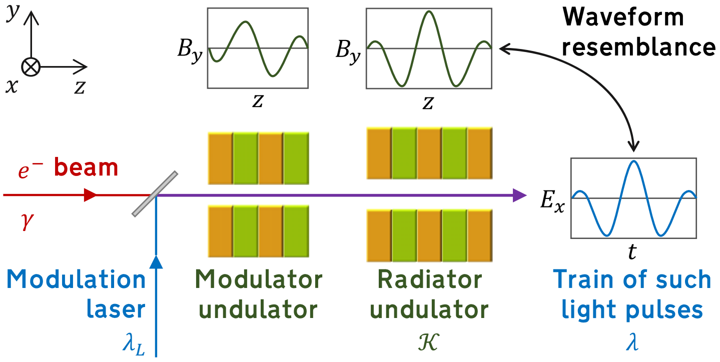

Figure 2. Waveform control with compact undulators

to radiate, the total number of wavefronts (i.e. the total number of optical cycles) increases. As illustrated by the simulation in Fig. 1(a), the number of wavefronts increases with the number of undulator periods. As a result, an FEL pulse typically contains at least tens or hundreds of optical cycles, and this limits the possibility of producing shorter FEL pulses.

Meanwhile, the novel undulator concepts provide a theoretical basis for generating *single-cycle* FEL pulses. This can be seen as a *paradigm shift* in accelerator physics.

2. Examples of Novel Concepts

2.1. Chirped Microbunching

This concept is detailed in Refs. [4, 6, 7], and its essence is illustrated in Fig. 1(b). It relies on *chirped microbunching*, whereby the microbunches are spaced at *varying* (instead of uniform) intervals. Once such microbunching is prepared by a *prebunching mechanism* (not shown here), the electron beam is sent through a *tapered* (instead of uniform) undulator. The interference of the wavefronts emitted by the electrons in the undulator then results in an intense isolated *single-cycle* light pulse.

There are three preconditions to be satisfied. First, the number of microbunches should be similar to the number of undulator periods. Second, the nth spacing between the microbunches, λ_n, should equal the resonant wavelength at the nth period of the tapered undulator. Third, the variation of λ_n with n should be as large and rapid as possible.

2.2. Waveform Control with Compact Undulators

This concept is detailed in Refs. [3, 5, 8], and shown schematically in Fig. 2. It deploys two *single-period* undulators, known as the *modulator* and the *radiator*. Each of them has a *tailored* magnetic field profile.

In the modulator, the modulation laser interacts with and imparts an energy modulation to the electron beam. In the subsequent drift space, ballistic bunching occurs, thus converting the energy modulation into a density modulation (uniform microbunching). In the radiator, each microbunch emits a single-cycle light pulse.

As shown analytically in Ref. [8], the electric field of the emitted light pulse has an almost *identical* waveform as the magnetic field of the radiator. This enables the direct control of the optical waveform. The reproducibility of the optical waveform from pulse to pulse yields CEP stability.

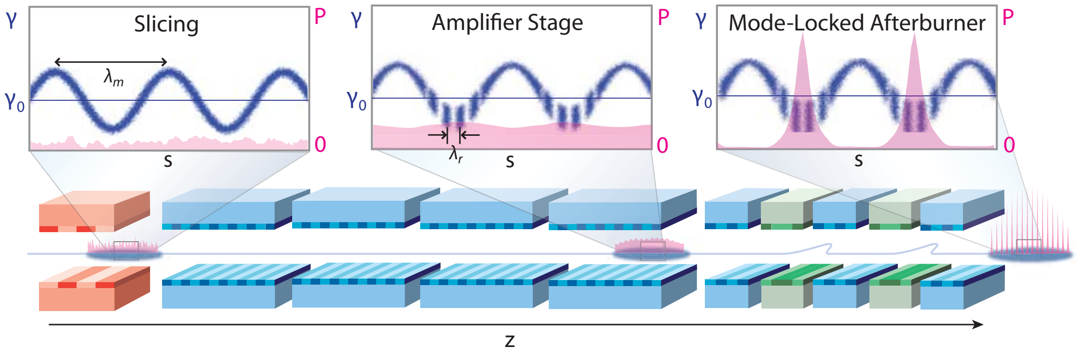

Figure 3. Mode-locked free-electron laser

2.3. Mode-Locked Free-Electron Laser

This concept is detailed in Refs. [1, 2], and shown schematically in Fig. 3. First, the electron beam is sent through the *energy modulator* where it develops a sinusoidal energy modulation. Next, the electron beam enters a normal FEL amplifier. Within this *amplifier stage*, the regions of the electron beam corresponding to the minima of the energy modulation develop the strongest microbunching, so that a periodic microbunching comb structure develops.

Once this comb structure is sufficiently well developed, but before any saturation of the FEL process, the electron beam is injected into a *mode-locked afterburner.* The afterburner comprises a series of few-period undulator segments separated by magnetic chicanes. The chicanes are configured to maintain the overlapping between the electron comb structure and a similar comb in the temporal profile of the radiation intensity. This overlapping allows the radiation comb to grow exponentially in power until saturation. The result is a train of intense few-cycle light pulses. The number of cycles in the light pulse can be reduced by decreasing the number of periods in each undulator segment of the afterburner. Simulations [1, 2] show that this technique has the potential to achieve *sub-attosecond* pulse duration.

3. Summary and Outlook

This article has surveyed three novel concepts for producing intense attosecond light pulses in undulators. These concepts are an important breakthrough for three reasons.

First, they have the potential to overcome the limitations of HHG, yielding a shorter pulse duration and higher pulse energy. Taking advantage of the FEL principle, they offer an unprecedented brilliance amongst laboratory x-ray sources.

Second, they shift the paradigm that FEL pulses must contain at least tens or hundreds of optical cycles, paving the way to obtaining *single-cycle* FEL pulses. This reduces the pulse duration from the *femtosecond* to the *attosecond* regime, making the FEL a powerful tool for attosecond science.

Third, the direct control over the radiation waveform enables CEP stability, which is essential for the reproducible guiding of atomic processes in attosecond science.

The immediate goal of the LUSIA collaboration is to demonstrate and refine the concepts by conducting proof-of-principle experiments at the **P**hoto-**I**njector **T**est Facility in **Z**euthen (PITZ), which is located at the DESY research centre in Zeuthen, Germany. Furthermore, the concepts could potentially be applied to the design of the future Soft X-ray Laser (SXL) facility [21] at the MAX IV Laboratory in Lund, Sweden.

4. Acknowledgment

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