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In Free-electron Lasers (FELs), a relativistic electron beam is injected into the periodic magnetic field of an undulator. This induces transverse velocity components in the electrons‘ motion, causing them to oscillate. This oscillatory motion allows the electrons to couple with the transverse components of a co-propagating radiation field. During one undulator period, the radiation field slips ahead of the electron beam by one wavelength. Notably, after half a period, the radiation field has slipped by 180 degrees, but the electrons' transverse velocity has reversed. As a result, the energy exchange between the electrons and the field is maintained, accumulating resonantly over multiple periods. The change in energy depends primarily on the initial phase relationship between the electron and the radiation field at the undulator entrance.

With sufficiently high radiation power and a high-quality electron beam (low energy spread), the sinusoidal energy modulation shifts the electrons longitudinally, where higher-energy electrons move forward while lower-energy ones fall back. This leads to the formation of a micro-bunching structure in the current profile, which emits coherently, amplifying the radiation field. This enhances the feedback loop between energy modulation, micro-bunching formation, and coherent emission, resulting in exponential growth in the FEL process. At saturation, the beam is strongly bunched, producing coherent emission.

During this process, the radiation field can only slip by one wavelength per undulator period, limiting the interaction length. In the X-ray regime, this leads to the formation of a single radiation spike, typically lasting a few hundred attoseconds. However, in normal operation, multiple independently formed spikes can occur throughout the electron bunch, typically 20-100 fs in duration. If the electron beam can be manipulated to support lasing in only a short subsection, a single X-ray spike can be generate with attosecond pulse duration.

The most straightforward method to achieve this is through non-linear compression, where a single current spike of a few kA is produced, followed by a low-current trailing tail that does not support lasing [1]. This method is robust against machine jitter, in contrast to low-charge operation and full-linear compression. Other methods include manipulating the electron bunch by emittance spoiler foils [2] or inducing a notch in the induced energy spread in the so-called laser heater [3]. More efficient methods, especially for high-repetition FELs, rely on self-modulation schemes. One approach leverages naturally occurring current spikes at the head or tail of the bunch. The spike emits coherently in the IR or visible region, modulating the electron energy, which is then compressed into a local current spike [4]. Alternatively, a strong undulator taper can compensate for the changing beam energy during the radiation slippage, allowing the FEL process to occur only at locations with strong local energy chirp [5].

Self-modulation can also be achieved by manipulating the electron beam during its generation, where space charge forces induce similar energy modulation [6]. If this modulation is driven by an external laser [7,8] instead of self-modulation, the resulting attosecond pulse can be locked to the laser‘s timing, reducing the timing jitter caused by electron bunch arrival fluctuations.

All of the methods mentioned so far result in pulse durations dictated by the FEL process, selecting a single spike rather than altering the spike duration itself. The pulse duration is weakly dependent on beam parameters, requiring an eightfold increase in current to reduce pulse duration by a factor of two. Alternative approaches, such as strong superradiance, aim to achieve shorter pulses by exploiting power levels above FEL saturation [9]. However, this process is rather inefficient, requiring very long undulators, and it can be challenging to initiate the process.

Other short-pulse techniques can be realized using a pseudo-oscillator configuration, where the electron beam is delayed after passing through a short undulator section. This produces a train of attosecond pulses, analogous to laser oscillator modes, with pulse duration now determined by the low number of undulator period rather than the FEL process [10]. Combining this with current or energy modulation can further confine lasing to specific parts of the electron beam. In this configuration, the radiation slippage and electron beam delay must match for successful amplification, though modifications can be made to produce a single attosecond spike [11,12].

Experimentally, the attosecond research group at LCLS currently holds the record for the shortest X-ray pulse at 100 attoseconds. Other facilities, such as the European XFEL and SwissFEL, have also demonstrated attosecond pulse generation and made these pulses available for user experiments.

Suggested Reading:

[1] S. Huang et al, PRL 119, 154801 (2017)
[2] P. Emma et al, PRL 92, 074801 (2004)
[3] A. Marinelli et al, PRL 116, 254801 (2016)
[4] J. Duris et al, Nature Photonics 14, 30-36 (2020)
[5] J. Duris et al, PRAB 23, 020702 (2020)
[6] Z. Zhang et al, New J. of Phys. 22, 083030 (2020)
[7] E. L. Saldin et al, PRSTAB 9, 050702 (2006)
[8] A. Zholents, PRSTAB 8, 040701 (2005)
[9] Wang et al PRL132, 035002 (2024)
[10] N. R. Thompson et al, PRL 100, 203901 (2008)
[11] T. Tanaka et al, JSR 23, 1273 (2016)
[12] T. Tanaka, PRL 114, 044801 (2015)