TERAHERTZ PHOTONICS

Efficient free electron laser

A single-pass free electron laser operating at 0.16 THz with an energy efficiency of ~10% promises compact and high-power sources in the terahertz spectral region.

Lixin Yan and Zhuoyuan Liu

In contrast to the flourishing development of optical light–matter studies, which mainly focus on exciting and manipulating atoms and valence electrons, the progress in controlling collective motions and dynamics of phonons and magnons in materials has been hindered by the scarcity of suitable radiation sources[1] operating in the terahertz spectrum (0.1 to 10 THz). In addition, the growing demand for nonlinear and non-resonant excitation and control of materials requires terahertz sources with improved efficiency and higher output powers[2].

Now, writing in *Nature Photonics*, Fisher et al.[3] demonstrate a potential solution in the form of a compact, single-pass terahertz (THz) free electron laser (FEL) with extremely high energy efficiency.

Many efforts have been devoted to developing a compact, high-power and tunable terahertz source. Among them, popular optical approaches utilizing optical rectification[4] or parametric oscillation[5] have limitations on output power and efficiency due to the damage threshold of the gain medium. For vacuum electronics devices currently in the sub-THz frequency, it is challenging to extend operation to higher frequencies due to difficulties in decreasing the transverse aperture size and the peak power being limited by the energy of non-relativistic electron beams. FELs represent a valuable alternative as they can produce high brightness radiation spanning from the THz to hard X-ray frequencies[6]. In a FEL, as relativistic electrons travel through a periodically alternating magnetic structure, called an undulator, they emit synchrotron radiation. While the emitted radiation slips forward compared to the electrons, resonant amplification can take place when the radiation slippage is exactly odd multiples of the wavelength. However, in the long wavelength regime, THz FELs suffer from slippage effects and diffraction, where the amplified radiation slips forward and diverges, limiting the output peak power and overall efficiency.

Fisher et al. mitigate these detrimental effects and demonstrate a compact,

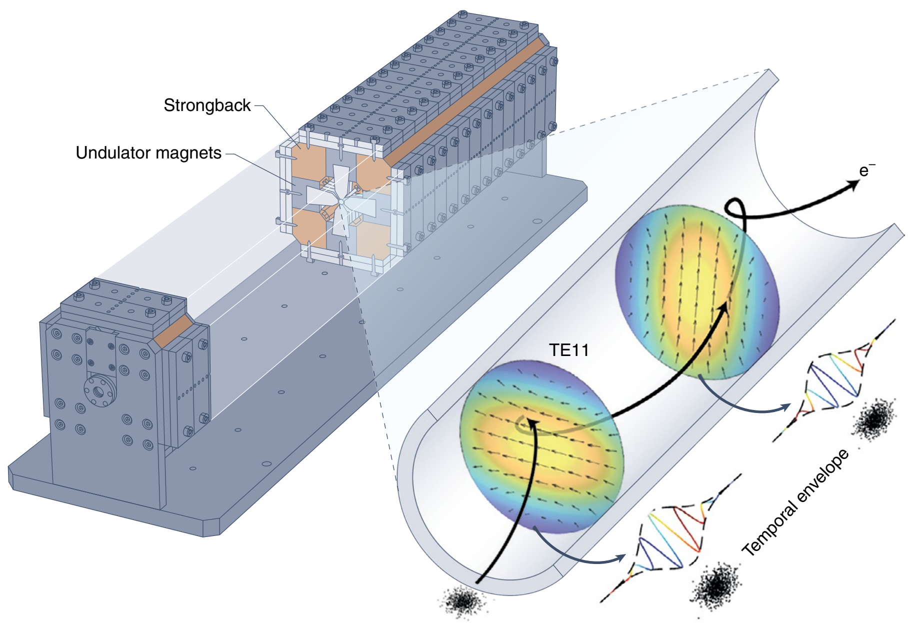

Fig. 1 | Schematic of the tapering-enhanced zero slippage THz FEL scheme. Electrons circulate in the waveguide and resonantly interact with the TE11 mode so that the field envelope remains temporally aligned to the beam. Credit: adapted from ref. [3], Springer Nature Ltd.

single-pass THz FEL with impressive efficiency up to ~10% using an undulator less than one metre long. Key to the high efficiency is the combination of two different concepts in accelerator physics to constrain both the transverse and longitudinal 'walk-off' between the electron beam and the radiation field.

The first concept is the use of a waveguide to confine the emitted radiation in the transverse direction and mitigate diffraction. The waveguide also provides the dispersion needed to match the group velocity of the radiation field with the average longitudinal velocity of the electron beam. In this way, the temporally synchronized electron beam interacts resonantly with the field and loses its power within a nearly single-cycle pulse (Fig.1), resulting in a much larger relative bandwidth (~50%) of the waveguide-FEL compared to the free space case, where bandwidth is inversely proportional to the number of undulator periods.

To maximize the energy extraction from the injected electron beam, the second critical element is the implementation of tapering-enhanced stimulated-superradiant amplification (TESSA)[7]. In this scheme, the magnetic field profile is parabolically tapered along the beamline to maintain resonant interaction with the decelerated electron beam. In a non-tapered case, the velocity mismatch between the (decelerating) electrons and the field leads to slippage in the ponderomotive phase and therefore results in reduced interaction and lower output pulse energy. These two concepts jointly ensure a zero-slippage condition where pondermotive phase shift and temporal walk-off between the electron and amplified field are eliminated, so that resonant energy extraction is guaranteed during the entire interaction.

To mitigate the effect of slippage, common THz FELs employ a rather long (many wavelengths) and low current electron beams to drive the FEL amplification in a resonant cavity. While high average power (around 10 W) THz radiation can be generated, this configuration lowers the peak power and the energy extraction efficiency. Moreover, the resonator configuration also requires a high-repetition-rate electron gun. By contrast, the enhanced interaction afforded by Fisher and colleagues' design allows the authors to achieve high energy efficiency and output peak power in just a single pass through the undulator.

Other schemes have also investigated ways to address the slippage problem in the THz, but have encountered difficulties in further improving the peak power and energy efficiency simultaneously. For example, another way to further boost the peak power and ease the detriment of slippage is to improve the longitudinal coherence of the electron beam. Advanced longitudinal bunch compression and shaping methods have been intensively studied[8,9]. The radiation power extracted from the pre-bunched beam is highly concentrated within a narrow frequency band, greatly enhancing the resonant interaction between THz and materials. While narrow-band THz pulses can be amplified through bunch shaping, the peak power of currently available broadband THz sources has remained relatively low due to the slippage effect, which limits the peak ponderomotive force available in THz-assisted non-resonant and strong-field control. Conversely, attempts to exploit the slippage effect have been put forward recently, where the constructive interference of different radiation frequency components of chirped micro-bunch in a strongly tapered undulator generates a quasi-half-cycle pulse[10,11]. However, this kind of scheme is based on spontaneous radiation, potentially leading to a reduced energy extraction efficiency and peak power available.

In their experiments carried out at the UCLA Pegasus beamline, Fisher et al. generate a compressed electron beam of 5.5 MeV with up to 200 pC of charge that is launched in a tapered helical undulator. A circular waveguide with 4.54 mm diameter serves as the THz waveguide supporting the TE11 mode, as well as a vacuum pipe in the undulator. The zero-slippage condition gives a resonant wavelength of 0.16 THz. Using phase space diagnostic tools, an average energy loss of 10% is measured with some electrons losing more than 20% of their kinetic energy. As measured by a pyroelectric detector, and considering losses in the THz transport lines, the authors estimate that the electron beam generates a nearly-single-cycle THz pulse with a total radiation energy of 50 μJ at the exit of the undulator. To further investigate the resonant nature of the interaction, the authors study the THz emission as a function of the injected beam energy. As the energy is tuned, the transition from the normal resonant condition to the zero-slippage condition is clearly observed at 0.16 THz as maximum electron deceleration and, as a consequence, maximum THz energy is detected.

While the current demonstration is successfully conducted at a rather low frequency of 0.16 THz, the proposed strategy has the potential to be extended to higher frequencies while maintaining a relatively high conversion efficiency with currently available technology. For higher frequencies, electron beams with higher energy and shorter bunch length are required and the diameter of the waveguide must be smaller in order to satisfy the zero-slippage condition. With the increasing beam energy, the ratio of the helical beam trajectory radius to the waveguide radius remains under ~0.5, which indicates experimental feasibility to extend operation to above 1 THz. However, the natural focussing strength of the undulator decreases with the increasing beam energy. Eventually, this method will be limited by the difficulty to match the beam size to avoid beam loss and the difficulty to further compress the electron bunch. At higher frequencies, bunch shaping techniques or external THz seeding could be considered as an option to trigger coherent radiation. The authors predict that a frequency scaling factor up to 100 may be achievable until significant beam loss occurs. Further improvement on tunability may also be attained with a planar undulator geometry and adjustable-gap waveguide[12].

In the past few decades, researchers have witnessed an ever-intensive race for compact, high-power and high-energy efficiency THz sources. This continuous effort is likely to transform the paradigm of THz science, as well as benefiting the scientific communities working in the fields of optics, electronics and accelerator physics. The results by Fisher et al. represent an important advance for the development of THz sources with high energy efficiency. The first demonstration of the TESSA concept in this high-gain regime represents important progress for THz science, while also opening up an appealing pathway for the future of FEL-based extreme ultraviolet/X-ray sources and inverse-FEL accelerators. ❐

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Published online: 12 May 2022
https://doi.org/10.1038/s41566-022-01007-w

References

1. Kampfrath, T. et al. *Nat. Photon.* **7**, 680–690 (2013).
2. von Hoegen, A. et al. *Nature* **555**, 79–82 (2018).
3. Fisher, A. et al. *Nat. Photon.* https://doi.org/10.1038/s41566-022-00995-z (2022).
4. Tian, Q. et al. *Opt. Express* **29**, 9624–9634 (2021).
5. Nawata, K. et al. *Sci. Rep.* **9**, 726 (2019).
6. Emma, P. et al. *Nat. Photon.* **4**, 641–647 (2010).
7. Duris, J. et al. *New J. Phys.* **17**, 63036 (2015).
8. Zhang, Z. et al. *Phys. Rev. Lett.* **116**, 184801 (2016).
9. Feng, H. et al. *Phys. Rev. Appl.* **15**, 44032 (2021).
10. Goryashko, V. A. *Phys. Rev. Accel. Beams* **20**, 80703 (2017).
11. Zhang, H. et al. *Phys. Rev. Accel. Beams* **23**, 20704 (2020).
12. Curry, E. et al. *New J. Phys.* **18**, 113045 (2016).

Competing interests

The authors declare no competing interests