The paradox of a free-electron laser without the laser

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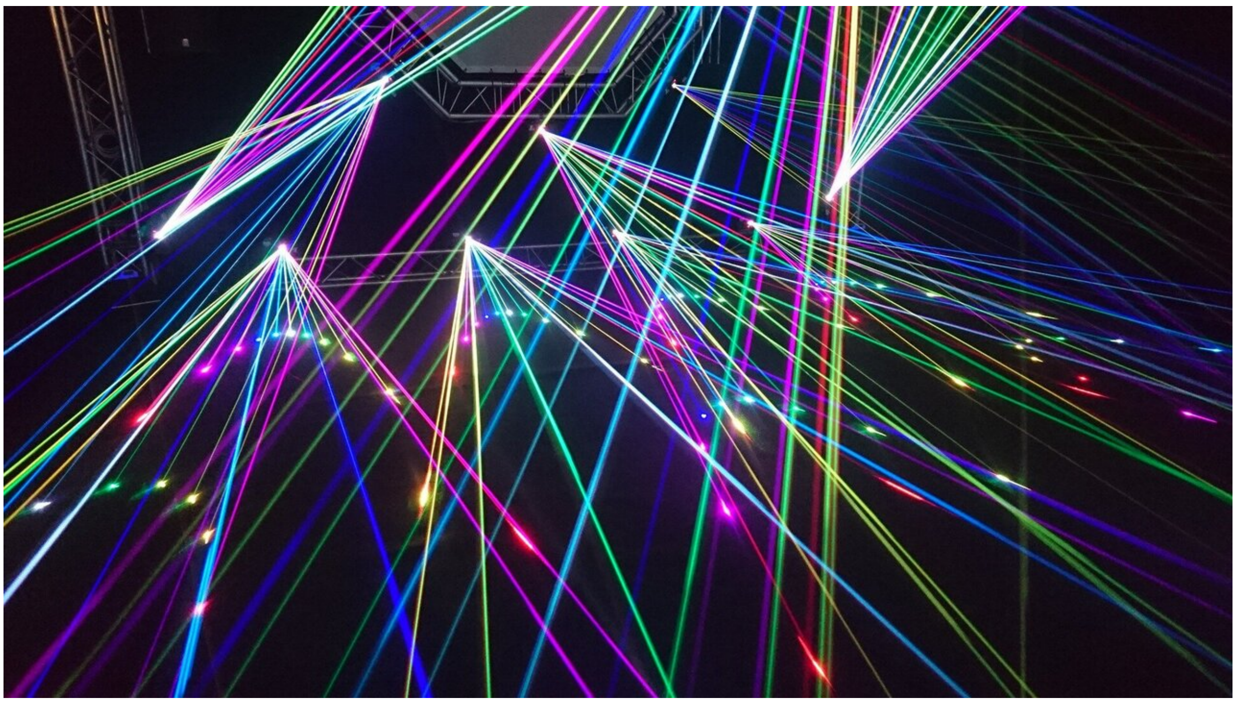

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A new way of producing coherent light in the ultra-violet spectral region, which points the way to developing brilliant table-top X-ray sources, has been produced in research led at the University of Strathclyde.

The scientists have developed a type of ultra-short wavelength coherent light source that does not require laser action to produce coherence.

Common electron-beam based light sources, known as fourth-generation light sources, are based on the free-electron laser (FEL), which uses an undulator to convert electron beam energy into X-rays.

Coherent light sources are powerful tools that enable research in many areas of medicine, biology, material sciences, chemistry and physics.

This new way of producing coherent radiation could revolutionise light sources, as it would make them highly compact, essentially table-top size, and capable of producing ultra-short duration pulses of light, much shorter than can be produced easily by any other means.

Making ultraviolet and X-ray coherent light sources more widely available would transform the way science is done; a university could have one of the devices in a single room, on a table top, for a reasonable price.

The group is now planning a proof-of-principle experiment in the ultraviolet spectral range to demonstrate this new way of producing coherent light. If successful, it should dramatically accelerate the development of even shorter wavelength coherent sources based on the same principle. The Strathclyde group has set up a facility to investigate these types of sources: the Scottish Centre for the Application of Plasma-based Accelerators (SCAPA), which hosts one of the highest power lasers in the UK.

The new research has been published in *Scientific Reports*, one of the *Nature* family of journals.

Professor Dino Jaroszynski, of Strathclyde's Department of Physics, led the research. He says that "this work significantly advances the state-of-the-art of synchrotron sources by proposing a new method of producing short-wavelength coherent radiation, using a short undulator and attosecond duration electron bunches."

"This is more compact and less demanding on the electron beam quality than free-electron lasers and could provide a paradigm shift in light sources, which would stimulate a new direction of research. It proposes to use bunch compression—as in chirped pulse amplification lasers—within the undulator to significantly enhance the radiation brightness."

"The new method presented would be of wide interest to a diverse community developing and using light sources."

In FELs, as in all lasers, the intensity of light is amplified by a feedback mechanism that locks the phases of individual radiators, which in this case are 'free' electrons. In the FEL, this is achieved by passing a high energy electron beam through the undulator, which is an array of alternating polarity magnets.

Light emitted from the electrons as they wiggle through the undulator creates a force called the ponderomotive force that bunches the electrons—some are slowed down, some are sped up, which causes bunching, similar to traffic on a motorway periodically slowing and speeding up.

Electrons passing through the undulator radiate incoherent light if they are uniformly distributed—for every electron that emits light, there is another electron that partially cancels out the light because they radiate out of phase. An analogy of this partial canceling out is rain on the sea: it produces many small ripples that partially cancel each other out, effectively quelling the waves—reducing their amplitude. In contrast, steady or pulsating wind will cause the waves to amplify through the mutual interaction of the wind with the sea.

In the FEL, electron bunching causes amplification of the light and the increase in its coherence, which usually takes a long time—thus very long undulators are required. In an X-ray FEL, the undulators can be more than a hundred meters long. The accelerators driving these X-ray FELs are kilometers long, which makes these devices very expensive and some of the largest instruments in the world.

However, using a free-electron laser to produce coherent radiation is not the only way; a "pre-bunched" beam or ultra-short electron bunch can also be used to achieve exactly the same coherence in a very short undulator that is less than a meter in length. As long as the electron bunch is shorter than the wavelength of the light produced by the undulator, it will automatically produce coherent light—all the light waves will add up or interfere constructively, which leads to very brilliant light with exactly the same properties of light from a laser.

The researchers have demonstrated theoretically that this can be achieved using a laser-plasma wakefield accelerator, which produces electron bunches that can have a length of a few tens of nanometres. They show that if these ultra-short bunches of high energy electrons pass through a short undulator, they can produce as may photons as a very expensive FEL can produce. Moreover, they have also shown that by producing an electron bunch that has an energy "chirp", they can ballistically compress the bunch to a very short duration inside the undulator, which provides a unique way of going to even shorter electron bunches and therefore produce even shorter wavelength light.

More information: Enrico Brunetti et al, Vacuum ultraviolet coherent undulator radiation from attosecond electron bunches, *Scientific Reports* (2021). DOI: 10.1038/s41598-021-93640-8

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