Towards full-coherence FELs

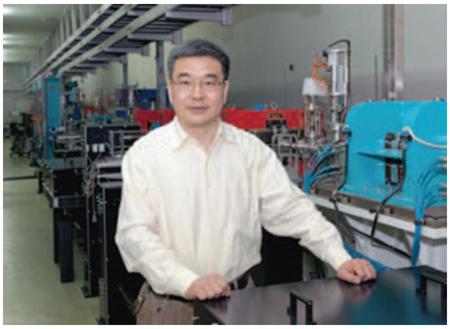
Zhentang Zhao from the Shanghai Institute of Applied Physics spoke with *Nature Photonics* about how he and his co-workers achieved first lasing in an echo-enabled harmonic generation free-electron laser.

What is your work about?

We have experimentally demonstrated first lasing from an echo-enabled harmonic generation (EEHG) free-electron laser (FEL) — a feat that could lead to the development of full-coherence FELs with short wavelengths and very high intensities. We performed our work using the Shanghai deep ultraviolet free-electron laser (SDUV-FEL) at the Shanghai Institute of Applied Physics (SINAP), which consists of a 135.4 MeV electron accelerator and an amplifier composed of a series of undulator magnets. The EEHG concept was first proposed in 2009 by Gennady Stupakov, a distinguished accelerator physicist at the Stanford Linear Accelerator Center. Our experimental approach is based on this idea and employs our experience on seeded FEL studies at the SDUV-FEL facility.

How does the EEHG scheme work?

The EEHG scheme is more complex than previous seeded FEL schemes such as direct seeding or high-gain harmonic generation (HGHG), particularly in the modulation section. The scheme consists of two modulators, two dispersive sections and a final radiator. The first dispersion section is chosen such that the energy modulation induced in the first modulator is macroscopically smeared out while imprinting very fine structure into the phase-space of the electron beam. The echo effect that occurs after the second modulator and the second dispersive section offers a smart way to generate microbunching in the beam distribution. The final radiator is similar to that used in self-amplified spontaneous emission (SASE), except that it is shorter and produces coherent radiation with the pre-bunched electron beam. The key advantage of EEHG over other seeded FEL schemes is that the amplitude of the achieved bunching factor decays slowly with the harmonic number. The important feature of our approach is that it ensures flexible tunability and a wide range of parameter choices, which is achieved by using a particularly strong field in the magnet chicane. Seeding is achieved by using a single laser to ensure the precise synchronization that is crucial for such FEL experiments.



WEICHENG HU

Zhentang Zhao inside the SDUV-FEL facility, where first lasing of the EEHG FEL scheme was demonstrated.

What did you achieve?

We demonstrated FEL lasing at the third harmonic of the seed laser with a gain of around 100,000 over the spontaneous radiation. We also amplified the FEL power to a level comparable to HGHG. In certain cases, the output bandwidth of the EEHG FEL was narrower than that of HGHG, owing to its weaker dependence on the energy chirp in the electron beam. The EEHG FEL output also exhibited excellent spectral stability and good intensity stability, at a level similar to HGHG and much better than that of SASE.

Did you experience many experimental difficulties?

The main difficulties were achieving transverse and temporal overlap between the electron beam and the laser beam in both modulator undulators, and making quantitative measurements of related key parameters. For the former, we achieved subpicosecond synchronization accuracy by combining a fast photodiode with coherent harmonic generation. For the latter, proper spreading of the electron beam energy and ensuring energy modulation amplitudes induced by both laser seeds were particularly crucial for optimization of the EEHG FEL. To this end, we developed a novel approach based on coherent harmonic generation to quantify these crucial parameters quickly and accurately.

What are the potential applications and challenges of your technique?

Given its advantage of remarkable upconversion efficiency at higher harmonics, the EEHG scheme is promising for generating fully coherent radiation at soft-X-ray wavelengths from conventional lasers that have only a single seeding stage. Such full-coherence X-ray pulses will benefit many applications, including soft-X-ray resonant inelastic scattering, spectroscopic studies of correlated electron materials, and holographic, diffractive or lensless imaging. The challenges lie in demonstrating EEHG at very high harmonics, where its advantages over other seeded FEL schemes will be particularly prominent. In such cases, the scheme may be limited by intra-beam scattering, shot noise of the electron beam or phase noise of the seed laser. Improvements in beam quality and/or additional radiator undulators will allow FEL saturation of EEHG to be achieved — and its characteristics explored — at the SDUV-FEL facility. Further shortening of the X-ray wavelength could be achieved by employing cascaded HGHG and EEHG schemes.

How will the SDUV-FEL facility benefit future research in China?

The SDUV-FEL is an ideal test bed for exploring the novel concepts and key technologies of seeded FELs. Two FEL projects in China — the Shanghai Soft-X-ray Free-Electron Laser Test Facility (SXFEL) and the Dalian Coherent Extreme-Ultraviolet User Facility — were approved in 2011. An X-ray FEL user facility has also been considered. We are planning to carry out experimental demonstrations in much higher harmonics at both the SDUV-FEL facility and at the SXFEL facility. The successful construction and operation of these centres will have a great impact on accelerator science and technology in China.

INTERVIEW BY RACHEL WON

Zhentang Zhao and co-workers have a Letter on their full-coherence free-electron laser on page 360 of this issue.